COST EFFECTIVENESS OF COMPOSITE MATERIALS
ON THE F-15 AND F-16 AIRCRAFTS

THESIS

Diana M. Bock
Captain, USAF

AFIT/GCA/LSY/89S-3

DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY
AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

The contents of the document are technically accurate, and no sensitive items, detrimental ideas, or deleterious information is contained therein. Furthermore, the views expressed in the document are those of the author and do not necessarily reflect the views of the School of Systems and Logistics, the Air University, the United States Air Force, or the Department of Defense.

AFIT/GCA/LSY/89S-3

COST EFFECTIVENESS OF COMPOSITE MATERIALS ON THE F-15 AND F-16 AIRCRAFTS

THESIS

Presented to the Faculty of the School of Logistics

of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the

Requirements for the Degree of

Master of Science in Cost Analysis

Diana M. Bock, B.S.

Captain, USAF

September 1989

Acknowledgments

I wish to extend gratitude to my thesis advisor, Captain Terry Adler, whose enthusiasm, encouragement, and constant support provided the incentive needed to successfully complete this research effort. I also thank the engineers at the Air Force Wright Aeronautical Laboratory for sharing their knowledge and years of experience concerning composite materials. Special recognition goes to Mr. Richard Murphy, who provided the expertise and guidance necessary to analyze numerous models in search for the "best" one and to Mr. Carroll Widenhouse, who contributed greatly to this effort, by helping me to obtain the maintenance data that was vital to the project. Further appreciation goes to my reader, Major John Stibravy, whose comments always led to significant improvements to the final product. Finally, I thank my husband George who endured it all with me.

Diana M. Bock

Preface

The purpose of this study was to determine the cost effectiveness of composite materials. With the Air Force committing to more extensive use of composites on the next generation of aircraft, and with the defense budget at decreasing levels, it becomes increasingly important to determine if composites provide the claimed cost advantage.

For those unfamiliar with technical material terms, a list of definitions has been provided in Appendix A. Figure 1 is included to show the relationship of composite materials to final design applications. Table 1 shows the types of reinforcements.

Diana M. Bock

Table of Contents

List of Figures

List of Tables

Abstract

The purpose of this research was to determine the cost effectiveness of composite materials by determing the significant cost drivers in a cost estimating model. Based on a review of historical literature and interviews, it was originally suspected that composite materials were not as cost effective as metal structures in terms of maintenance manhours.

The models developed in this project revealed that number of landings, flight hours, and sortie counts were the most significant cost drivers for maintaining the F-4 stabilator system, a metal structure, and the composite materials found on the horizontal and vertical stabilizers of the F-15 and F-16 aircrafts. The stabilator system on the F-4 was most respondent to the three cost drivers, as this structure required significantly more maintenance manhours than either the F-15 or F-16 parts. The F-16 horizontal stabilizer assembly was also sensitive to the cost drivers found, as this composite part had more maintenance manhours than the other three composite parts. The F-16 skins, vertical stabilizer assembly, and the F-15 torque box, vertical stabilizer and honeycomb assembly, and the F-15 torque box, horizontal stabilator assembly showed that regardless of the number of landings, flight hours, or sorties counts, the maintenance manhours remained constant, within the range of data for this project.

Cost Effectiveness of Composite Materials on the F-15 and F-16 Aircrafts

I. Introduction

General Issue

Composite material technology is designed to produce aircraft with such characteristics as light weight, high strength, and increased reliability, maintainability, and capability. Composites differ from conventional engineering materials in that a second material is added to conventional material so specific performance characteristics can be obtained that are not available from the first, unmodified material. This material technology is finding its way into a broad range of currently emerging aircraft, such as the YF-22A, the Advanced Tactical Fighter (ATF), the V-22 Osprey, and the LHX, light attack helicopter (8:70,73). According to Bruno Revellin-Falcoz, General echnical Director, Dassault-Breguet, France, combat aircraft of the year 2000 must be designed to face the threat from both high performance enemy aircraft and from a dense network of surface-to-air missiles (31:2). These requirements will lead to multi-mission aircraft incorporating the most advanced technology available in fields such as aerodynamics, propulsion, structures, avionics, and weapon systems. It is proposed that an integrated use of technology will result in additional performance improvements. Revellin-Falcoz suggests that the new aircraft, by its characteristics and performance, will widely surpass the operational efficiency of the present day combat aircraft. Future aircraft will surpass present day aircraft in many areas including high payload (armament and fuel) capacity, high performance with respect to range of action and autonomy, increased survivability provided by good visibility, effective electronic countermeasures, and long-range radar (31:4-5). Other features of future aircraft include reduced vulnerability resulting from a strong structure and reliable systems, ease of maintenance, deployment and implementation, and low cost for development, acquisition and implementation (31:4-5). A minimal number of new aircraft will, however, be needed to counter the threat of numerically superior opponents (31:2). Acquisition and Life Cycle Cost (LCC) of the new aircraft should therefore be minimized. This principle comes without any suggestion as to its achievement. As in the past, the combat aircraft of the future will continue to profit from significant developments currently underway, including those to come in the field of structures and materials (31:8). The main goals planned are:

a. Making the structure lighter.
b. Increasing its fatigue life and resistance to damage.
c. Reducing vulnerability.
d. Ease of manufacturing, inspection, testing, and maintainability and repairability.
e. Reduction of costs (31:2,9).

By relying on the latest advances in composite material technology, the Pentagon believes future aircraft can overcome the greater number of enemy weapons (18:76). During the past seven years, when the defense budget had risen from $217 billion to $290 billion annually, Congress would not have hesitated to approve funding for future aircraft (22:76). Recently, however, Congress actually provided less than zero real growth for defense in 1986. Thus, with the further Gramm-Rudman-Hollings automatic reductions for 1986, defense authority declined more than five percent in real terms (19:5-4). This decline in funding will make it more difficult for Congress to approve weapon systems that use expensive composite materials.

Proponents of new aircraft insist the United States will be vulnerable without the latest advances in electronics and weaponry. For instance, the Air Force needs "the revolutionary ATF to dominate the first quarter of the 21st century," said General Lawrence A. Skantze, head of the Air Force Systems Command (22;76). Special materials and new fuselage designs in the ATF will produce a stealth aircraft, unable to be detected by enemy radar and heat sensors. The pilot's job is also simplified. He will be able to "talk" to his plane, ordering data displayed on his helmet visor. In the LHX, sensors will read the pilot's eyes and point weapons where the pilot looks (22:76). Lawmakers and military experts disagree and argue that economics make it more prudent for the military to buy more of today's proven weapons. rather than explore advanced technology (18:76).

Despite the potential advantages of advanced technology, new planes can become so bulky and complex the they are prohibitively expensive. The ATF is estimated at about $35 million each - more than double the General Dynamics F-16. It will weigh twice as much as the F-16, making the ATF's profile easier for enemy aircraft to detect, charges William S. Lind, president of the Washington-based Military Reform Institute. Lind wanted to cancel the ATF for a simpler new fighter which he believed would be more effective. "When combat becomes dense," Lind argued, "individual aircraft characteristics wash out and numbers become vitally important" (22:80).

Background

Life Cycle Cost. In order to study cost effectiveness of composite materials, life cycle costs (LCC) must be explained so cost effectiveness can be defined in LCC terms. According to the Air Force Systems Command Cost Estimating Handbook (34), LCC captures the cost to develop, produce, operate, support, and dispose of a system. LCC elements follow the program life cycle which consists of the six milestones or phases: Concept Exploration (milestone 0), Demonstration and Validation (milestone 1), Full-Scale Development (milestone 2), Production and Deployment (milestone 3), and Operating and Support (milestone 4 and 5). Development costs occur during the Concept Exploration, Demonstration and Validation and Full-Scale Development phases. Production costs occur during the Full-Scale Development, Production and Deployment, and Operating and Support. Operating and Support costs occur during Production, Deployment, Operating and Support. Disposal costs occur during disposal. This acquisition life cycle is performed to reduce risk. Early in a program's life cycle, information is needed to produce accurate cost estimate figures, although the program is not yet precisely defined (1; 34:2-3 to 2-4).

The cost effectiveness of composite materials can be defined in terms of development, production, operation, support, and disposal. Research will emphasize cost effectiveness in Operation and Support terms. The AFSC Cost Estimating Handbook defines system Operating and Support costs as the added or variable costs of personnel, material, facilities, and other items needed for the peacetime operation, maintenance, and support of a system during activation, steady state operation, and disposal. Disposal costs, however, which are associated with system demilitarization, storage, and scrapping (excluding salvage value), are seldom estimated and included as part of Operation and Support costs. The operation, maintenance, and support can further be defined as a function of reliability and maintainability. Both factors are interrelated and affect the operational effectiveness of a system. Reliability determines how often maintenance will be performed, while maintainability dictates how much that maintenance will cost. Operational effectiveness of a system is a function of availability, the probability that a system will be in an operating state at the start of a mission, and dependability, the probability that the system will remain in a satisfactory operating state. Dependability is derived from reliability. Both reliability and maintainability impact availability and affect operational effectiveness. Reliability and maintainability are attributes which can be designed into a system and which depend on the environment in which the system operates and is repaired. Research will focus on operational reliability and maintainability of composite materials. Therefore, cost effectiveness of composite material parts will be defined in terms of operational reliability and maintainability (34:10-3; 19:10-3; 3:6-R-3).

Reliability is the probability that a system will perform its intended function under specified conditions for a certain length of time or a certain number of cycles (29). Reliability parameters include logistics, mission, contractual, and operational reliability requirements. Operational reliability is used to describe reliability performance when a weapon system is operated in a planned environment. It also describes needed levels of performance and includes effects of item design, quality, installation, environment, maintenance policy, and repair. Typical operational reliability terms are: Mean Time Between Maintenance (MTBM), Mean Time Between Demand (MTBD), Mean Time Between Removal (MTBR), and Mean Time Between Critical Failure (MTBCF) (29).

Maintainability is the probability that an item will be retained in or restored to a specific condition within a given period of time, when maintenance is performed in accordance with prescribed procedures and resources (6). Maintainability parameters are specified in three basic levels of repair (29):

Organizational Level - Repair at the system location.

Intermediate Level - Repair at an intermediate shop facility which has more extensive capability.

Depot Level - Highly specialized repair facility capable of making repairs at all hardware levels.

Current Air Force policy has promoted the concept of two level maintenance in place of the traditional three level system. Another method of classifying where maintenance actions will occur is by on-equipment and off-equipment. Under this classification, these terms are defined as (29):

On-equipment - Maintenance actions accomplished on complete end items.

Off-equipment - In-shop maintenance actions performed on removed components.

Maintainability parameters include Mean Time to Repair (MTTR), and Mean Maintenance Manhours (MMMH) for both classifications (29).

The defense posture of the United States depends on countering a numerically superior enemy. To accomplish this, weapon systems are required to sustain operational performance over time. Highly reliable and maintainable systems offer the capability to defeat a numerically superior enemy. Air Force goals for reliability and maintainability are (18:2):

Increase combat capability.

Decrease vulnerability of the combat support structure.

Decrease mobility requirements per unit.

Decrease manpower requirements per unit of output.

Decrease costs.

In order to continue with this study, it is important to first have a general understanding of the development of composite materials, their basic characteristics, and their performance in current and future aircraft applications.

Development. Combining two or more materials to form a new material with enhanced properties has existed since the time of the Ancient Jewish slaves, who, under the Pharaoh's rule, mixed chopped straw in mortar as a means of enhancing a brick's structural integrity (36:1). In construction of weapons, the Mongul bow was assembled with animal tendons, wood, and silk bonded together with an adhesive. In more recent times, linoleum can be quoted as a composite material. However, analytical determination of composite material properties did not begin until the 1800's. J.C. Maxwell in 1873 and Lord Rayleigh in 1892 computed the ability of composites, consisting of a matrix, to conduct electrical current. Analysis of mechanical properties apparently originated with a famous paper by Albert Einstein in 1906 in which he computed the effective viscosity of a fluid containing a small amount of rigid spherical particles. Until about 1960, work was primarily concerned with matrix/particle composites and polycrystalline aggregates. A technology began to emerge about 1960 with the advent of modern fiber composites consisting of very stiff and strong aligned fibers (glass, boron, carbon, and graphite) in a polymeric matrix and later in a light weight metal matrix (23:481; 36:1).

The Basics. Composites differ from conventional engineering materials in that a second material is added to obtain specific performance characteristics not available from the first, unmodified material (Figure 1). The second material is added to provide strength and stiffness, as with carbon fibers or other reinforcements in thermoplastic or thermoset polymer resin; to enhance toughness, as with whiskers in ceramic composites; or to control heat expansion, as with silicon-carbide particles in metal matrix composites. Candidate material for matrices and reinforcements is limitless. The boundary between the matrix and the reinforcement, or interface, is controlled to obtain the desired properties from a given pair of materials (20:15-16).

The Matrix. The matrix serves several critical functions in overall composite performance beyond simply holding reinforcements in place. Since many reinforcements tend to be brittle, the matrix protects the reinforcement's surface against abrasion or environmental corrosion, both of which can initiate fracture. To reduce failure in the matrix, adhesion to fibers or other reinforcements must be coupled with sufficient matrix strength. In the event of fiber breakage, thematrix redistributes the load among neighboring reinforcements as well as both halves of the broken reinforcements (20:19-20; 33:1259).

Reinforcing for Performance. Transfer of loads and improvement in fracture toughness provided by the matrix and reinforcement are

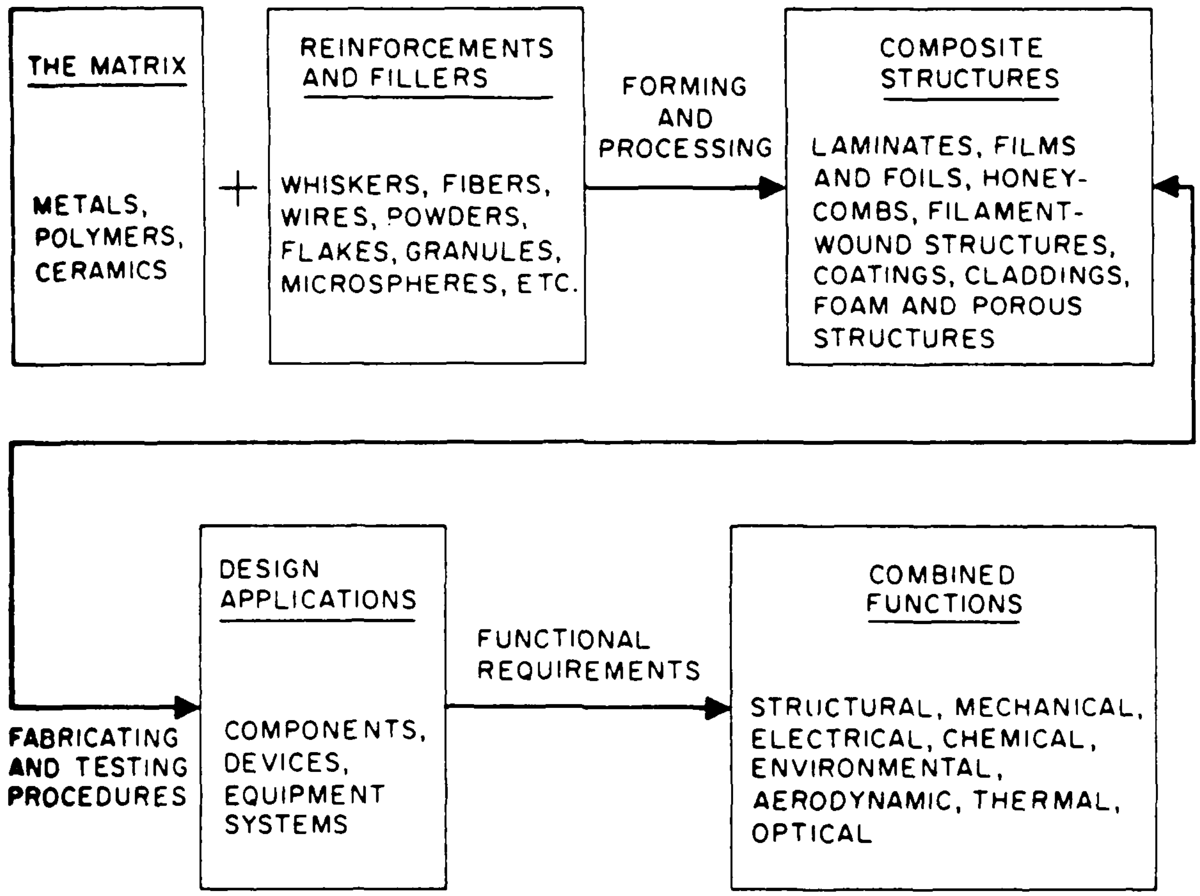

Fig. 1. Relationship of Composite Materials to Final Design Applications (32:3)

necessary prerequisites for high specific strength and stiffness most commonly associated with composites. However, it is the reinforcement that is primarily responsible for such structural properties as strength and stiffness. They are also a cost driver in how effective systems can be supported as the reinforcement is claimed to be the key to optimizing cost/performance for a given application, although this cost performance is not quantitatively documented (20:20,25).

Reinforcements are of the following types: fibers, whiskers, flakes, and spheres (Table 1). Fiber reinforcements dominate the composite industry. High-stiffness boron filaments, reported in 1959, were already established as reinforcements in the 1960's for such applications as the F-111B wing tips, the F-100 wing cover, and the T-39 center wing box. Carbon/graphite fibers also originated in the late 1950's. While not offering the absolute strength and stiffness of boron, carbon/graphite fibers reportedly are significantly less expensive. This cost/performance balance, which is not substantiated, has made carbon/graphite preeminent in high-end advanced-composite applications (20:21).

Table I

Types of Reinforcements

Fibers	Flakes	Spheres	Whiskers
Glass	Glass	Glass	Ceramics
Boron	Mica	Plastic	Graphite
Aramid	Metal	Carbon	Alumina
		Ceramic	Silicon
			(12:20)

Current Trends. Despite initial high cost, the need to reduce weight and increase aircraft performance first drove the aerospace industry to composites. Today, it is claimed that a spiral of applications have driven basic costs down, but just how far down has not been assessed (12:36).

According to Dr. R. C. Forney, Executive Vice-President, DuPont Company, there are general economic trends wherein composites can expect a significant growth potential. There will be a trend of shifting from large, mass produced units to small, flexible units. Thus, where in the past one had available a limited selection, the future would be characterized by variety and diversity (6:26). The aircraft industry is also learning that composites can be expensive as cited by Mr. Bruce Peterman, Vice-President Production Planning and Program Manager for Cessna Aircraft Company:

> That drives us to two things - finding better ways to manufacture composite structures for lower cost and being selective in the applications. What's important is looking at the weight advantages gained from composites for the cost incurred to develop the part. The answer is that we are finding some places where we probably shouldn't have used composites. (2:50)

Research and development have proven composites are so valuable that Aeronatical Systems Division engineers plan to use one class of matrix composite, organic or plastic, for a large percent of the ATF, the next generation Air Force fighter. The ATF will be able to cruise supersonically at 1.5 times the speed of sound or 1300 mph. It is expected to fly twice as many combat missions in a given period time of existing fighters. It will also have triple the engine reliability of the current F-15 Air Force fighter, designed in 1969. To create a plane with both range and speed, the ATF is being forged from new composite materials and, at $35 million each, will be the most expensive fighter plane ever to take to the air. After centuries of development, the ATF represents the pinnacle of aviation achievement (6:366; 8:73;).

Despite cost considerations, pioneering work is forging ahead to develop unique, new thermoplastic matrix composites to be used in forward cooler sections of aircraft engines. Lab scientists study these new thermoplastic composites because they are resistant to solvents such as a paint stripper, although it was not mentioned whether present composites resist solvents. Thermoplastics can be repaired by just reheating and reforming. Air Force material engineers feel that thermoplastics would save the Air Force money in acquisition, manufacture, and maintenance of aircraft parts (4:366). The value of composite applications are in terms of performance, not dollars. Cost advantages from composite use are not cited. In fact, specific dollar amounts are not referred to. Reasons for avoiding cost advantages can only be speculated. Could it be cost advantages can not be determined or would not render the desired answer?

Future Trends. The development of carbon fiber/thermoplastic matrix composites is being embraced with much enthusiasm as demonstrations show promise for low-cost, high-speed fabrication, extended product life cycles, and improved performance. As an extension of this research, new thermoplastic composites are available as commingled hybrid yarns. By binding resin powders to carbon fibers, highly fabric-like materials may be produced (7:27; 21:57).

These hybrid yarns can be made into various forms, such as woven, braided, and knitted structures. Subsequent molding at specified temperatures and pressure conditions provide easily reproducible, high-quality composites. The hybrid yarn concept originated as a means of providing low-weight, high-temperature capability for the proposed ATF. Key advantages of hybrid yarn products include flexibility and drape for complex contoured shapes, ease of processing, and reproducibility of quality composite parts. Commingled yarns may also be used for specialized sewing and stitching thread applications. Although a new technology, hybrid yarns have been embraced by a broad diversity of design fields. The fabricability, toughness, and high-temperature performance of hybrid yarns has fostered active interest in fuselage and wing applications in the aerospace area (7:27).

Problem Statement

Scientists claim the use of composite materials can be cost effective, yet this cost effectiveness is not expressed as a function of how changes in independent cost drivers (composite material parts) affect operational reliability and maintainability factors such as Mean Manhours to Repair (MMR), Mean Time Between Failure (MTBF), Mean Time Between Corrective Maintenance Actions (MTBMA), Mean Time Between Removal (MTBR), and Mean Time Between Maintenance (MTBM) (12:36; 20:21,25,34; 22:76; 24:94,96; 35:1214).

Literature Review

The ability to analyze the effect of composite materials on operational reliability and maintainability costs has been hampered by a number of factors. The primary problem is lack of actual cost data. This problem exists because a limited number of aircraft have been produced which use composites for primary structures or which use a high percentage of composites for secondary structures. Although use of composites on older aircraft is limited, this lack of cost data may be attributed to lack of documenting cost data. For whatever the reason, the lack of historical cost data makes cost analysis of composite materials difficult. This problem has surfaced numerous times during literature review searches. Presently, funding issues and budget cuts make it appropriate to question the costs of composite materials (4:I1-2).

Analysis of existing data is complicated because it represents widely varying types and manufacturing methods. Applications for future composite materials differ significantly from existing composites because the material and manufacturing technology are evolving. For example, it becomes difficult to determine a cost for graphite epoxy when over three-hundred types exist. Manufacturing techniques are not consistent for all composite types and costs vary from material to material (4:I1-2).

Further complications result from the common problem of inconsistencies with historical data formats and cost tracking procedures. The historical aircraft data bases often used for cost analysis do not always include aircraft that use significant amounts of composite materials. Because of technology changes, historical data is quickly rendered obsolete. Among the principle advanced composite materials cost tracking tools, a majority focus on establishing only production costs of advanced composite airframe structures. The research and development, and operating and support costs are then addressed in life cycle cost models. A fundamental problem arises when using an airframe cost model developed from "all metal" airframe data to predict costs of an airframe using advanced composite materials. Such use assumes that the relationships developed previously for metal airframes are now appropriate for composite airframes. However, advanced composite structures have different parameters that influence the costs versus all metal structures. Parameters include type of material and composite fabrication technique. Manufacturing techniques may be automated, semi-automated, or entirely manual. The appropriate manufacturing technique employed is determined by the design of the structure and type of material. Currently, approximately 90 percent of all composite structures are built using manual labor. Although studies have not confirmed exactly the cost differential, the extensive amount of hand labor required for composite materials increases the manufacturing costs as compared to metal structures. Manufacturing cost impacts for composite materials showed that fabrication and testing increased because of the more involved process and testing required by composites. Conversely, assembly and spares decrease costs because fewer parts, fasteners, and inventory parts are required (4:VI-2-5,10-11).

There is also a problem concerning the lack of sufficient depth of analysis of significant elements of operation and support. Operation and support could be generated with greater sensitivity to the reliability and maintainability of hardware. However, there exists no standard cost element structure to use as a guide - a comprehensive list from which to select the elements significance in a particular case (25:12).

When considering the effect of operational reliability and maintainability on aircraft maintenance manpower, two models evaluated by Rand Corporation provided fair coverage of cost relationships. The Rand Logistics Support Cost model provided some sensitivity to cost parameters, but it based costs on manhours rather than manpower and did not address manpower needed for repair of shop replaceable units. The Rand Logistics Composite model did relate component reliability and maintainability characteristics to manpower, but only for conventional maintenance concepts. Both models provided partial coverage of the relevant relationship, but neither was complete. Rand concluded that the available models (Logistics Support Cost Model and Logistics Composite Model) were generally inadequate. There is no single cost element for which all potential cost drivers can be addressed. For most problems, it may not be possible to generate a completely satisfactory cost estimate for generalized models alone. The prediction of the real cost changes associated with operational reliability and maintainability depends on the analyst's ability to supplement models with additional analysis and interpretation of study results (25:6,21-23).

A Short-Cut Estimating Methodology (SCEM) has been developed by the Directorate of Advanced Systems, Cost Deputy for Development Planning, Wright-Patterson AFB, OH to provide LCC using a minimum of system inputs and calculations (10). The SCEM, dated May 1971, reduces to graphic form several techniques and data from various cost models and manuals (not specified). Estimates prepared through SCEM compare very closely with those developed through more lengthy computerized procedures. The effect of graphite epoxy application on non-recurring and recurring airframe costs were graphed as percent composite in airframe as the independent variable and percent cost increase of the independent variable. These complexity factors are based on data resulting from a study on the application of advanced materials to a specific aircraft design. Required inputs to the model are percent of composite material in airframe. The airframe cost is increased by the percent of composite material content in the airframe (10:1,3).

Research Objective

The objective of this research is to define cost effectiveness of composite materials in Operating and Support terms, specifically, reliability and maintainability, develop a cost estimating model in this area for composites, and determine the significant cost drivers in developing the model. This model could then be used by Program Office personnel to predict Operation and Support costs with regard to reliability and maintainability of composite materials used on future Air Force aircraft.

Investigative Questions

Answers to following questions will provide the means to fulfill the research objectives:

1. How can cost effectiveness be defined according to reliability and maintainability factors of Operating and Support costs?

2. What are the reliability and maintainability costs included in Operating and Support costs?

3. What are the significant cost drivers in developing an estimating model for composite materials?

4. How can the significant cost drivers be related in the cost estimating model to accurately predict future composite Operating and Support costs?

5. How can the cost estimating model be evaluated as a predictor of Operating and Support costs for future aircraft?

Scope and Limitations

Few available cost tools use actual costs of individual composite structures. The task of estimating costs of composite materials must begin by determining whether actual cost data for composites are available and if this data can be used for cost estimating. In reviewing the cost impacts of using composite materials versus conventional metals, total fabrication and manufacturing cost must be considered. It must be determined whether composite structures are more expensive when manufacturing costs are involved. With composites, the price of raw material coupled with the cost to manufacture will be a major concern for estimating future airframe structures. The critically of the structure or component to the performance of a given mission will dictate whether high material and manufacturing costs can be tolerated. Price of raw materials is not the only factor in determining the choice of material for an application. Total cost, raw material and manufacturing must be considered when evaluating costs of airframe structures, particularly those that include a substantial amount of composite materials (1:I1-7).

The estimated cost effect of two types of composites (graphite epoxy and boron fiber epoxy) will be incorporated into a cost estimating model to determine how Operating and Support costs respond.

There are four major limitations that could reduce the accuracy of the cost model. First, weather conditions may influence the performance of composite materials. For example, aircraft located at Nellis AFB, Nevada, may develop different maintenance problems than the aircraft located at Eglin AFB, Florida. It will not be possible to accurately measure the impact of weather on composite material performance. Second, aircraft age may influence the type of maintenance required and frequency of occurrence. Maintenance data collection records do not maintain aircraft age so this influence can not be measured. Third, the nature of maintenance data itself imposes a degree of inaccuracy on the model. The maintenance data maintained is reasonably accurate, but a certain unknown percentage of maintenance actions are never recorded by the operating base and the depot. This percentage of missing data can not be determined, but it will be assumed it is small enough not to grossly distort the cost model. Lastly, there are hundreds of different types of composite materials, with new composites constantly being developed. This research will only include the two types of composite materials mentioned. Because each composite is structurally different, the findings of this research should not be implied to all composites known today and yet to be developed. Every composite possesses its own performance properties, making broad generalizations about composites inappropriate.

Summary

Materials technology has advanced tremendously from the days of mixing straw and mortar. Composite materials are becoming prominent in the aerospace industry because of the structural characteristics they offer. The lighter the material used, the faster and more fuel efficient an aircraft can be. The stronger the materials used, the more reliable an aircraft can be. Despite this desire to create efficient and reliable aircraft, cost factors must be considered. The U.S. Government must receive the best weapon system for the money. To expand this concept of cost factors for composites, the following chapter will discuss cost estimating tools that can be applied to present and future aircraft composite structures.

II. Basic Methodology

Introduction

The objective of this research was to develop a cost prediction model for composite material aircraft parts based upon operational reliability and maintainability parameters. This model is a cost estimating relationship (CER) describing a numerical relationship which is useful in computing estimated costs. Composite material parts chosen for research were selected with the assistance of Air Force Wright Laboratory personnel (AFWAL) (30). Parts selected were: the horizontal and vertical stabilizer (graphite epoxy) found on the F-16 and the horizontal and vertical stabilizer (boron fiber epoxy) found on the F-15 as seen in Figures 2 and 3. These composite parts were chosen for their extensive maintenance data history (of at least 8 years) which provided data required for developing a model. It would have been difficult to obtain extensive historical data on a new aircraft. For comparison purposes, metallic structures from the F-4 (Figure 4) were compared to the composite material parts from the F-16 and F-15. This comparison is necessary to provide possible recommendations that composite material parts could have been replaced with metals.

The tool used to develop the model for composite materials was parametric statistical methods. A population parameter, such as the mean or standard deviation, is identified, a random sample is collected, a sample point is selected, and a sampling distribution is used to construct hypothesis-testing decision rules. Certain properties of a parent population must hold before hypothesis testing can be performed, usually that the sample observations come from a normally distributed

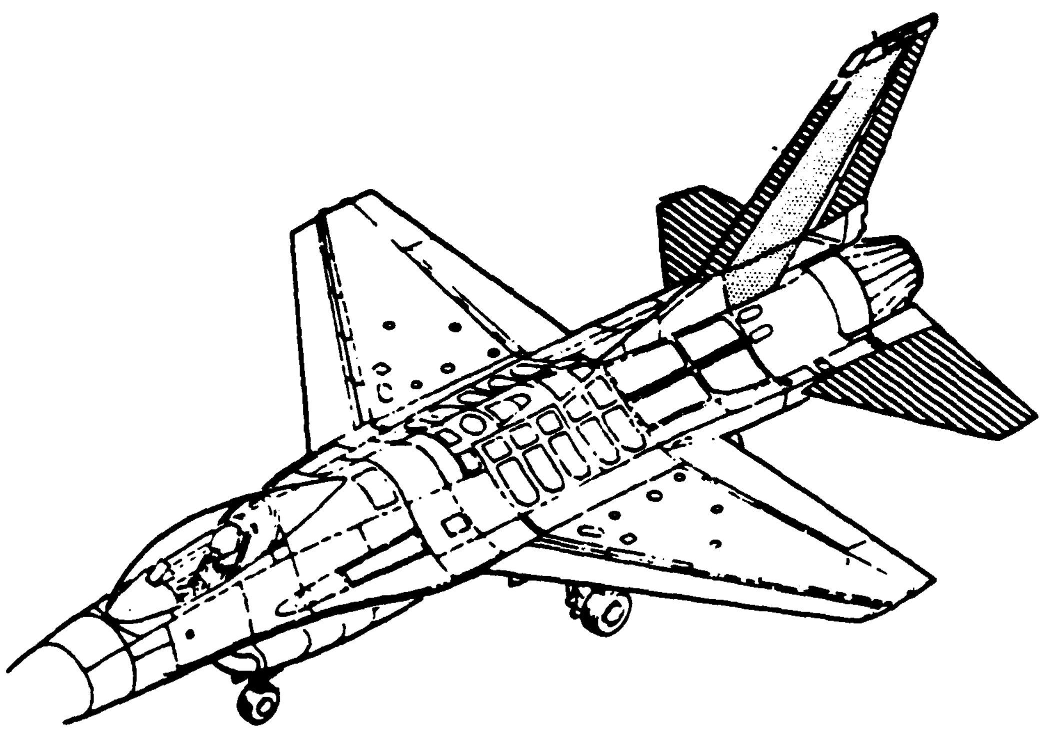

Fig. 2. F-16 Vertical and Horizontal Stabilizer (17:7-1)

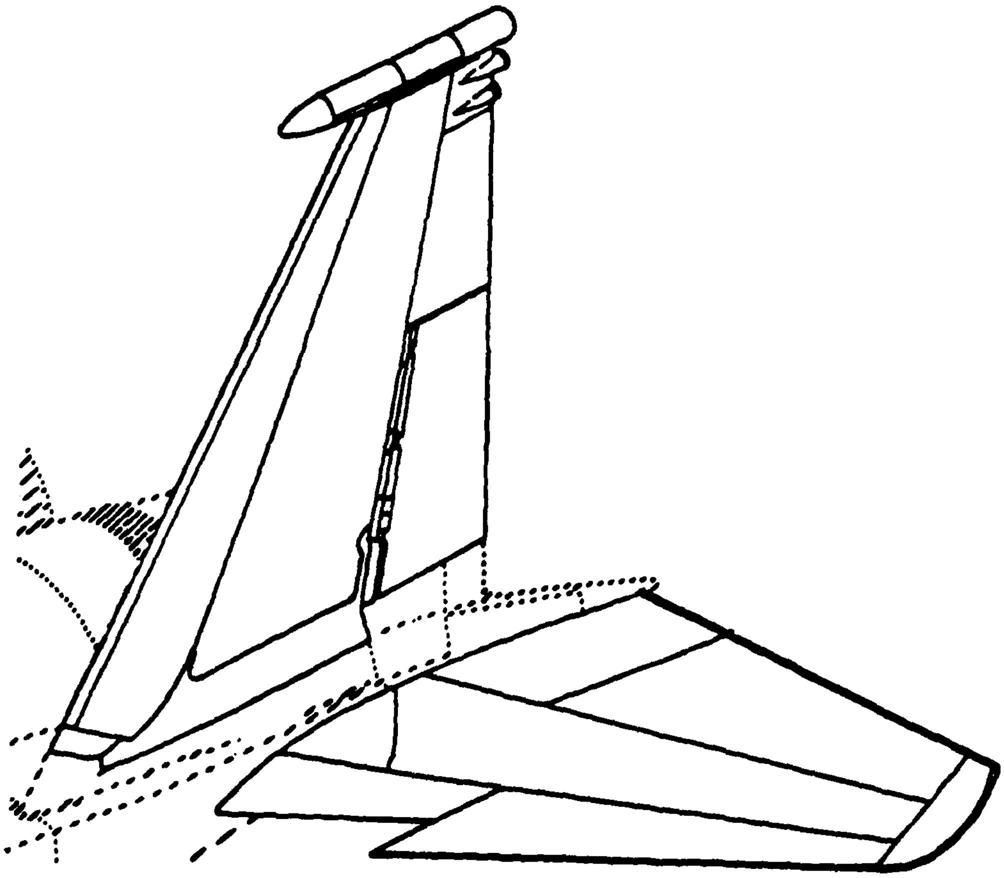

Fig. 3. F-15 Vertical and Horizontal Stabilizer (16:3-123)

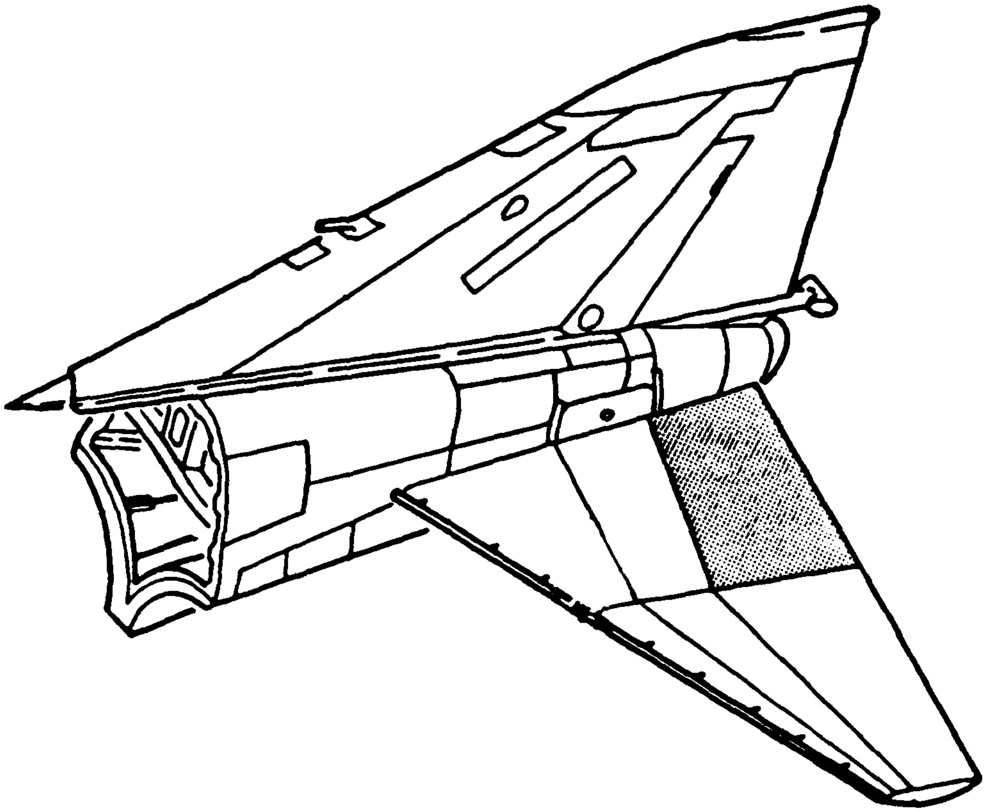

Fig. 4. F-4 Stabilator System (15:3-2)

population. Regression Analysis was then used to estimate the average value of a given variable, called the dependent variable, in terms of the known values of one or more other variables, called the independent variable. This relationship between the dependent and independent variables was expressed by determining a mathematical equation that connected them. This approach involved collecting data consisting of the independent variables, which included the selected aircraft parts, flight hours, sorties, landings, total maintenance actions, type 1 failures (inherent failures), type 2 failures (induced failures), type 6 failures (no defect or other failure), Mean Time Between Maintenance (MTBM), and Mean Time Between Removal (MTBR). Removal counts were also used in model analysis as a replacement for MTBR. Event counts also replaced MTBM. The dependent variable was total maintenance manhours, a parameter driven by the independent variables by means of Multiple Regression Analysis. Other cost parameters which drive reliability and maintainability, such as spare and support equipment, and training and logistic support cannot be quantified because subjective variables affect them (27).

Data Collection

Since the parameters considered were major cost drivers of Operation and Maintenance cost, emphasis was placed on finding the most up to date information. The Maintenance and Operational Data Access System (MODAS) provided the required maintenance data by Work Unit Code (WUC) (13; 15; 16; 17;). The MODAS is an on-line, interactive data storage and access system for the storage and processing of maintenance and operational data on selected USAF weapon systems. Headquarters Air

Force Logistics Command is responsible for handling interface requirements (37). Each independent variable has a unique WUC which can be obtained by referring to the Technical Manual for Aircraft Maintenance for each aircraft type (15:14-002,14-003,14-005; 16:11-007,14-002; 17:11-022,14-007,14-008,14-011). Other important data obtained from the MODAS was the type of maintenance action, when the discrepancy was discovered, how the aircraft malfunctioned, the name of the operating base, and the Major Command the aircraft belonged to. This information was used, not as specific cost drivers, but as subjective data to summarize composite material problems by Major Command, location, and type of malfunction. The MODAS provided on-line specific maintenance data, for the past two years, for every specific aircraft in the United States Air Force inventory. Stored microfiche provided maintenance data back to 1981.

There has been no previous study devoted to developing a model for composite material parts. It was necessary to simultaneously consider all variables which have been "assumed" to have an influence on the dependent variable, and let statistics and techniques lead the direction of obtaining equations that can yield the best possible predictions. The independent variables were not considered one at a time or in pairs or in any other grouping, but they were all considered simultaneously to determine their compound effect on the parameter to be estimated.

It can be shown that a dependent variable can be highly correlated to one independent variable and no apparent correlation exists between another independent variable, but the compound effect of both variables (or many variables) can have a significant effect on the dependent variable. Therefore, when multiple independent variables are considered, the dependent variable should not be regressed against each independent variable in determining the form of the equation. For this study, the following functional form will be considered as a means of estimating composite material costs:

$$Y = bo + b1x1 + b2x2 + b3x3 + \ldots$$

Here, Y stands for the dependent variable, xi's for the independent variables, bo as a constant of the y-intercept, and bi's as the regression coefficients for each independent variable. The method to be used to obtain the best possible prediction will be the method of least squares. To determine how "good" the estimates are, statistics will be used to verify the "goodness" of fit of the relationship between the independent and dependent variables (27).

Statistical Tests

The level of confidence, or significance level, used for model analysis is chosen by the individual analyst's judgement. According to Aeronautical Systems Division Cost Analysis personnel, the level of confidence depends on the nature of the data and the judgement of the analyst (26). For the models involved with this project, the following levels of confidence were chosen based on generally accepted rules of thumb excepted by the Cost Analysis field and because of the importance of reducing type I errors (27).

T-Value. The T-value statistic will be significant at 80% or greater for each independent variable in the selected model. The T-value tests the individual significance of each independent variable as a cost driver. A T-value with an 80% confidence level says the probability of rejecting a true null hypothesis (Type I error) is 20%. The T-value tests the null hypothesis that the regression coefficient of each individual variable in the selected model is insignificant (equal to 0), against the alternate hypothesis that the regression coefficient is significant (not equal to 0). A T-value is calculated from the parameter estimates and its associated standard error. A T-value which exceeds the T-distribution table value will allow rejection of the null hypothesis. When the null hypothesis can be rejected, the individual independent variable can be considered a significant cost driver (27). The T-value is defined by:

$$\text{T-Value} = \frac{bi - 0}{Sbi}$$

To compute a 95% confidence interval for each parameter estimate, the following is used:

$$bi - t\ alpha/2;n-p\ Sbi \leq Bi \leq bi - t\ alpha/2;n-p\ Sbi$$

This interval provides the numbers which the Bi value will lie between, at 95% confidence. If the interval does not contain zero, it can be concluded, at the .05 significance level, that Bi is not zero. However, in multiple regression, a Bi that is not zero does not imply that it is useful for prediction purposes. For multiple regression, hypothesis testing for regression coefficients should be done jointly (27).

F-Value. The F-value will be significant at 90% or greater. This criteria determines how significant the selected model is. An F-value with a 90% confidence level says the probability of rejecting a true null hypothesis is 10%. The F-value tests the null hypothesis, that the regression coefficients in the selected model are insignificant (equal to 0), against the alternate hypothesis that at least one of the regression coefficients (excluding the y-intercept) is significant (not equal to 0). An F-value calculated from the statistics based on the selected model which exceeds the F-value from the F-distribution table will allow rejection of the null hypothesis. When the null hypothesis can be rejected, the compound effects of all independent variables are considered significant cost drivers (27).

R-Squared (R2). The value of R2 will be at 90% or greater. R2 measures the proportion of the total variability in the dependent random variable which is explained by the independent variables through the fitting of the regression line. The closer R2 is to 100%, the stronger the linear relationship between the random dependent variable and the independent variables in the selected model (27).

Adjusted R-Square (*R2). The value of *R2 will be as close to R2 as possible. *R2 is an indicator of the significance of adding variables to the selected model. As significant independent variables are added to the model, both R2 and *R2 will increase. However, as insignificant independent variables are added to the model, R2 will increase but *R2 will decrease (27).

Coefficient of Variation (CV). The CV value should be less than 20%. Multiplying CV by 2 gives the 95% prediction interval bounds, in terms of percentage, around the center of the data. The smaller CV is, the greater the possibility of getting good estimates of the independent variables at the center of the data (27).

Outlying Data. The ideal model has no outliers or collinearity. Correlation among independent variables describes collinearity. Outlying, or extreme, observations are well separated from the remainder of the data. Outlying observations may affect the fitted least squares regression function. An observation may be outlying with respect to the x values, the Y values, or both.

Outliers With Respect to x. Outliers with respect to x, the independent variable, are detected by a leverage value. A leverage value greater than 2 (parameters/observations) indicates outlying x values. The leverage value for an x observation indicates outlying observations by measuring the distance between an x value and the mean of all x values for the number of observations. Leverage values are a function of only x values and measure the importance of x values in determing how important the actual regression line is in affecting the fitted (predicted) regression line. A large leverage value indicates the actual regression line is important in determining the predicted regression line (28:400-403).

Outliers With Respect to Y. When considering outliers with respect to Y, the dependent variable, a studentized residual is used. This residual indicates a residual divided by the standard error of the distribution from which that residual was drawn. The studentized residual will be at a t-significance of 95% (28:405).

Cooksd. The Cooksd is used to measure the overall impact an observation can have on the estimated regression coefficients. Cooksd does not follow the F-distribution. However, to assess the magnitude of Cooksd, the F (parameters, observations - parameters) distribution is used. If a Cooksd value is less than the F-distribution value at 50%, that observation is not considered to be influential. If a Cooksd value is greater than the F-distribution at 90%, that observation would be considered to be influential. An outlying influential observation should not automatically be discarded. The observation may be correct, but may represent an unlikely or unusual event. Unless a gross measurement error can be found, influential observations should not be removed from the data set. Since there was no evidence of gross measurement error, potential outlying observations were not removed from the data. To determine the F-distribution values, the models discussed in Chapter 4 used 3 degrees of freedom in the numerator and 33 in the denominator. The size of the Cooksd value depends on the size of the residual and the leverage value (28:408-409).

Collinearity. To test for collinearity, condition numbers were obtained. Without considering the y-intercept term, condition numbers less than 10 indicated no correlation between variables. Condition numbers show collinearity among all independent variables as oppossed to obtaining correlation between pairs, as given by the Pearson correlation matrix. Another measure of collinearity in a model is the tolerance values. A tolerance value of 0 means there is high collinearity among the independent variables, where a tolerance value of 1 means there is no collinearity. It is rare to have a model with no collinearity, but it is important to reduce a model's collinearity to the greatest extent possible. Correlation between the independent variables will not inhibit the ability to obtain a good least squares best fit; however, the estimated regression coefficients may have large sampling variablity and will vary widely from one sample to another when collinearity exits (27; 28:384-385).

Summary

This Chapter discussed the basic methodology and collection of data that was used in developing a model for estimating cost effectiveness of composite materials. The model was evaluated against the statistical criteria from this Chapter, as a way to verify its soundness as a predictor of maintenance manhours. Chapter 3 will further discuss, in detail, the maintenance data obtained from research and how that data was used in deriving the independent variables.

III. Data Base Collection

This chapter will review the sources that were used to solve the research questions. The primary source of data collection was maintenance data history maintained for the F-4, F-15, and F-16 aircrafts.

The Maintenance and Operational Data (MODAS) System is an on-line, interactive data storage and access system for the storage and processing of maintenance and operational data on selected Air Force weapon systems. Its primary function is to provide a data base management system with automated analytical capability to support Reliability and Maintainability, Product Improvement, and Product Performance Programs established by the Air Force and the Air Force Logistics Command (AFLC). The Maintenance Policy Division, Headquarters AFLC/MMDA, has the overall responsibility for handling interface requirements for users of the system. A primary input to the MODAS is the Maintenance Data and Collection System (MDCS), which is considered to be the backbone of the Air Force maintenance data collection and analysis effort for operational weapon systems and support systems. MODAS consists of seven separate data bases. Many of the data bases provide the latest 24 months of maintenance data and six are updated monthly. The MODAS was chosen as a source of information because it provided the most recent maintenance data available (13:1-1,2-1,2-3).

The Maintenance Data and Collection System (MDCS) is used by the Air Force for maintenance data collection and analysis of operational weapon systems and support equipment. The MDCS provides a data base of information that is accessible to base managers and supervisors responsible for controlling maintenance operations. Major Commands also use the MDCS for controlling maintenance programs. Air Force Logistics Command is designed as the focal point for MDCS data processing and analysis (13:2-1).

MDCS data is transmitted daily from base level activities. When a maintenance action is completed on an aircraft, the AFTO Form 349, Maintenance Data Collection Record, is completed by base maintenance personnel responsible for working on the aircraft. The AFTO 349 documents, among other information, type of maintenance action, aircraft serial number, aircraft model number, sortie number, location, work unit code, action taken, start and stop times for maintenance actions, discrepancy description, and corrective action description (14:7).

Information obtained from the MODAS included monthly summary failure data presented by manhour counts and by failure counts. Output was obtained from a wide range of parameters. Aircraft selection was done by a five digit code for each aircraft model number. Work unit codes for each aircraft appears on Table II. Data for the F-4 aircraft was obtained for F004C, F004D, F004E and F004G. For the F-15 aircraft, designator codes were F015A, F015B, F015C, F015D, and F015E. The F-16 designator codes were F016A, F016B, F016C, and F016D. The summary failure data was also selected by component level which corresponded to the entire aircraft, an aircraft system, subsystem, or the four- and five-digit WUCs. Because of the specific parts selected for research, the five digit WUCs were used for the F-15 and F-16 composite aircraft parts selected as independent variables. Five digit WUCs for the F-15 torque box, vertical stabilizer, and torque box, honeycomb assembly, horizontal stabilator assembly were selected. For the F-16, the five digit WUC was selected for the skins, vertical stabilizer assembly, and the horizontal stabilizer assembly. However, the F-4 used a three digit code for the stabilator system because this system was most comparable as a metal structure to the composite parts on the F-15 and F-16. All WUCs were verified by AFWAL personnel (30).

Table II

Work Unit Codes for Aircraft Components

Aircraft	Work Unit Code	Component Nomenclature
F-4	14300	Stabilator System
F-15	11GKB	Torque Box, Stabilizer Vertical
F-15	14CAD	Honeycomb Assembly, Torque Box, Horizontal Stabilator Assembly
F-16	11JAC	Skins, Vertical Stabilizer
F-16	14CBO	Horizontal Stabilizer Assembly

(15:14-002; 16:11-007,14-002; 17:11-020,14-007)

Base location was another parameter selection. In all cases, summary failure data was obtained for the entire aircraft fleet, which included all base locations for an aircraft. Summary failure data reports covered a 24 month period, ranging from February 1987 to January 1989. The summary failure report by manhours included flight hours, maintenance manhours for on and off-equipment, on-equipment events, and mean manhours to repair. The summary failure report by failure counts provided information for the same time period, aircraft, and work unit codes, but included removal counts, and failure counts by type.

Another report obtained from the MODAS was monthly reliability status for the most recent 24 month period, February 1987 through January 1989. This output provided calculations for mean time between maintenance action (MTBM), mean time between removals (MTBR), and mean time between events (MTBE). The MTBM calculations were made by dividing flight hours by failure counts using failure and flight hour counts from the summary failure data file. MTBR was calculated as flight hours divided by removal counts. MTBE was calculated as flight hours divided by event counts. Similar to the summary failure reports, parameters for selection included aircraft, component level, and base location. These parameters remained the same when requesting reliability output. A different parameter from the summary failure data was type of failure. Reliability output was selected by type of failure - type 1 for inherent failures, type 2 for induced failures, and type 6 for no defect or other failures. This type of failure is used as a designator to distinguish how a system malfunctioned. Each failure type actually represents numerous other codes which can be translated into a particular system malfunction. For a type 1 failure, some examples of system malfunctions are faulty tube, combustion case burn, turbine damage due to metal failure, and low oil pressure. Type 2 failures are not caused by normal operating of the system, but are rather caused by human error or weather conditions and include flameout, loose, damaged or missing hardware, contaminated oil, and condensation. Type 6 failures are not really system failures, but include maintenance actions which render the system inoperable. Such failures include servicing, foreign object (no damage), no defect-component removed/reinstalled to facilitate other maintenance, and no defect-indicated defect caused by associated equipment malfunction (14:33-42). Because the MODAS provided data for a 24 month period, historical maintenance data was obtained from the DO-56T, Standard Reliability and Maintainability Report. This data was also maintained by Headquarters AFLC/MMDA and was read on microfiche (37). DO-56T data was maintained by aircraft model similar to the model designator codes used for the MODAS. The only exception was for the F-15. DO-56T documented data for the F-15C model and summarized all other F-15 models under the F-15 designator. The time period of data was semi-annual from 31 December 1988 to 31 December 1987. From 1 January 1986 to 31 December 1981, data was maintained yearly. Maintenance data for a period earlier than 1981 was not maintained for five digit WUCs. Because research questions dealt with mostly five digit WUCs, data before 1981 could not be obtained. Therefore, the overall time frame for maintenance data collected covered the 1 January 1981 to 31 December 1988 period.

DO-56T data included aircraft inventory counts, operating or flight hours, sortie counts, number of landings, MTBM, mean man hours by operating hour and shop time, event counts, total maintenance actions, and hours for on-equipment and shop repair. A major limitation of the DO-56T data was missing information. Reportedly, all the maintenance data for the F-16C and F-16D, 1981-1986, had been stolen and could not be replaced (5). Also, for 1986, data for the F-15C was not obtained because of a change in engine codes. Additionally, when there was no maintenance action for a particular WUC, nothing was reported on the DO-56T. Therefore, partial information was obtained for the F-15 for the years 1984 and 1987. For the F-16, partial information was obtained for the 1985 through the 1981 period.

The objective of collecting maintenance data was to obtain dependent and independent variables that could be used in the CER model, which is the topic of Chapter 4. After reviewing the available maintenance data, nine independent variables and one dependent variable were selected for model development. The dependent variable was total base level maintenance actions. Manhours were chosen as the dependent variable because it represents the cost, in terms of hours, of maintaining composite and metal aircraft structures in the field. Nine independent variables were chosen, with assistance from the Air Force System Command Cost Estimating Handbook (34), that were determined to most influence the number of manhours required to maintain a structure. The independent variables are flight hours, number of sorties, number of landings, total maintenance actions, failure counts for types 1, 2, and 6, MTBM, and MTBR. Table III represents all variables.

Table III

Independent and Dependent Variables for Model Development

Independent Variables	Dependent Variable
Flight Hours	Total Maintenance Manhours
Number of Sorties	
Number of Landings	
Total Maintenance Actions	
Type 1 Failures	
Type 2 Failures	
Type 6 Failures	
MTBR or removal count	
MTBM or event count	

Maintenance hour and flight hour counts for the 1981 through the 1988 period came from the Summary Maintenance report for manhours and from the DO-56T. The number of sorties, landings and total maintenance actions came from the DO-56T reports. MTBM was calculated on the reliability report and the DO-56T, but were calculated differently on each report. The reliability report calculated MTBM as flight hours divided by failure count. The DO-56T calculated MTBM as flight hours divided by failure count. Because the DO-56T covered a longer time frame, MTBM came from the DO-56T. Failure counts, by type, came from the Summary Maintenance Data for Failures because the DO-56T did not record failure counts by type. MTBR came only from the reliability report because the DO-56T did not record this data either.

After all of the maintenance data was obtained, it was summarized by aircraft and WUC. Total maintenance manhours, flight hours, sorties, landings, and total maintenance actions were then expressed in terms of an average per year. An average per year was used for these variables to normalize the highs and lows of the data over the eight year range. Because failure count by type was obtained for only two years, it was not necessary to average the data. Table IV summarizes maintenance data as an average for the eight year period.

Table IV

Summary Maintenance Data by Aircraft and Work Unit Code
Average for the Eight Year Period, 1981-1988

Aircraft/WUC	Independent Variables	Dependent Variable
F-4/14300	Flight Hours 243276	Total Maintenance Manhours 77493

- continued -

Table IV -continued

Aircraft/WUC	Independent Variables	Dependent Variable
F-4/14300	Sorties 194704	
	Landings 212744	
	Maintenance Actions 8111	
	Type 1 Failures 2482	
	Type 2 Failures 126	
	Type 6 Failures 1304	
	MTBR 182	
	MTBM 33	
F-15/11GKB	Flight Hours 143152	Total Maintenance Manhours 335
	Sorties 108650	
	Landings 115869	
	Maintenance Actions 57	
	Type 1 Failures not reported	
	Type 2 Failures not reported	
	Type 6 Failures not reported	
	MTBR not reported	
	MTBM 2695	
F-15/14CAD	Flight Hours 143152	Total Maintenance Manhours 256
	Sorties 108650	
	Landings 115869	
	Maintenance Actions 27	
	Type 1 Failures not reported	
	Type 2 Failures not reported	

- continued -

Table IV - continued

Aircraft/WUC	Independent Variable	Dependent Variable
F-15/14CAD	Type 6 Failures not reported	
	MTBR not reported	
	MTBM 5532	
F-16/11JAC	Flight Hours 173478	Total Maintenance Manhours 225
	Sorties 126929	
	Landings 134795	
	Maintenance Actions 28	
	Type 1 Failures 43	
	Type 2 Failures 0	
	Type 6 Failures 5	
	MTBR 133747	
	MTBM 6455	
F-16/14CBO	Flight Hours 173478	Total Maintenance Manhours 4100
	Sorties 126929	
	Landings 134795	
	Maintenance Actions 480	
	Type 1 Failures 344	
	Type 2 Failures 34	
	Type 6 Failures 5	
	MTBR 3082	
	MTBM 434	

For the F-4, flight ranged from a low of 7,720 hours for the F-4C for 1988 to a high of 120,753 hours for the F-4E in 1983. Sorties ranged from a low count of 6,098 for the F-4C for 1988 and to a high count of 98274 for the F-4E for 1983. Landings had a low of 6,295, again for the F-4C for 1988, and a high of 106,233 for the F-4E for 1983. Total maintenance actions ranged from a low of 106 to 5,472 for the F-4C and F-4E, respectively, for the same years. Maintenance manhours had a low of 1109.2 for the F-4C for 1988 and a high 13031.6 for the F-4E for 1983. The low and high range in data may be caused by the fact that the F-4C had an inventory count of 32 for 1988 and the F-4E had an inventory count of 484 for 1983, as presented in Table VI. The range of data is summarized in Table V.

For the F-15 torque box, vertical stabilizer, the low flight hours was 45,738 for the F-15C for 1981 and the high was 97,912 for the F-15C for 1985. Sorties ranged from a low of 33,596 for the F-15C for 1981 to a high of 73019 for the F-15C for 1985. Landings ranged from 34,433 for the F-15C for 1981 to a high of 79,809 for the F-15C for 1987. Maintenance actions had a low of 7 for the F-15C for 1981 and high of 102 for the F-15C for 1988. Finally, manhours ranged from a low of 100.1 for the F-15C to a high 652.8 for the F-15C for 1988. The F-15C had an inventory of 166 for 1981, the smallest inventory for either the F-15C or F-15. This inventory count, as shown in Table VI, is compared to the F-15C inventory for 1985, 1987 and 1988 which was 303, 327, and 353 respectively. For the F-15 honey comb assembly, horizontal stabilator assembly, the data range for flight hours, sorties, and landings was the same as the torque box because information for these variables was documented by aircraft. However, maintenance actions differed for the honeycomb assembly. The low maintenance actions were 5 for the F-15C for 1981 and the high was 36 for the F-15 for 1986. Total maintenance manhours ranged from 80.7 for the F-15C for 1985 to 423.3

for the F-15 for 1984. One contributing factor for the difference in the range of data for flight hours, sorties, and landings is the inventory count which varies from year to year. With more or less inventory, flight hours, sorties, and landings will vary. The variance in data for total maintenance actions and total maintenance manhours will be affected by the particular aircraft structure. This data is summarized in Table V.

For the F-16, the horizontal stabilizer assembly had flight hours that ranged from 5,896 for the F-16D for 1987 to 174,324 for the F-16A for 1987. This variance could be attributed to the large difference in aircraft inventory as presented in Table VI. The F-16D had 36 aircraft in inventory for 1987 while the F-16A had 526. Sortie counts ranged from a low of 4,177 for the F-16D for 1987 to a high of 126,451 for the F-16A for 1987. Landings had a low count 6,107 for the F-16D for 1987 and a high count of 127,841 for the F-16A for 1987. Again, the large variances in the high and low counts could be attributed to the invertories for the F-16A and F-16D aircrafts. Maintenance actions varied from a low of 15 for the F-16B for 1981 to a high of 569 for the F-16A for 1987. The F-16B inventory for 1981 was 58 as compared to the F-16A inventory of 526. Maintenance manhours ranged from a low of 18 for the F-16C for 1987 to a high of 5,628.8 for the F-16A for 1984. Again, inventory differed between the two models, as the F-16C had only 231 aircraft. For the F-16 skins, vertical stabilizer assembly, data ranged the same for the flight hours, sorties, and landings. Maintenance actions differed as the low was 2 for the F-16B for 1981 and the high was 52 for the F-16A for 1987. The range from 2 to 52 differed greatly from the 15 to 569 for the horizontal stabilizer. Maintenance manhours for the skins ranged from 7 for the F-16B for 1981 to 643.1 for the F-16A for 1987. This range was in great contrast to the 18 to 5628.8 range for the horizontal stabilizer. This range of data is summarized in Table V.

Table V

Range of Data for Independent and Dependent Variables
By Aircraft and Work Unit Code

Aircraft/ WUC	Independent Variables	Range of Data Low to High
F-4/14300	Flight Hours	7720(F-4C), 120753(F-4E)
	Sorties	6098(F-4C), 98274(F-4E)
	Landings	6295(F-4C), 106233(F-4E)
	Maintenance Actions	106(F-4C), 5472(F-4E)
	Dependent Variable	
	Maintenance Manhours	1109(F-4C), 13032(F-4E)
F-15/11GKB	Flight Hours	45738(F-15C), 97912(F-15C)
	Sorties	33596(F-15C), 73019(F-15C)
	Landings	34433(F-15C), 79809(F-15C)
	Maintenance Actions	7(F-15C), 102(F-15C)
	Dependent Variable	
	Maintenance Manhours	100(F-15C), 653(F-15C)
F-15/14CAD	Flight Hours	Same as above
	Sorties	Same as above
	Landings	Same as above
	Maintenance Actions	5 (F-15C), 36(F-15C)

- continued -

Table V -continued

Aircraft/ WUC	Independent Variables	Range of Data Low to High
F-15/14CAD	Dependent Variable	
	Maintenance Manhours	81(F-15C), 423(F-15)
F-16/14CBO	Flight Hours	5896(F-16D), 174324(F-16A)
	Sorties	4177(F-16D), 126451(F-16A)
	Landings	6107(F-16D), 127841(F-16A)
	Maintenance Actions	15(F-16B), 569(F-16A)
	Dependent Variable	
	Maintenance Manhours	18(F-16C), 5629(F-16A)
F-16/11JAC	Flight Hours	5896(F-16D), 174324(F-16A)
	Sorties	4177(F-16D), 126451(F-16A)
	Landings	6107(F-16D), 127841(F-16A)
	Maintenance Actions	2(F-16B), 52(F-16A)
	Dependent Variable	
	Maintenance Manhours	7(F-16B), 643(F-16A)

Table VI

Aircraft Inventory Counts
By Aircraft Model, for 1981-1988

Aircraft Model	81	82	83	Year 84	85	86	87	88
F-4C	273	275	269	276	253	183	81	32
F-4D	419	415	428	423	382	364	325	277
F-4E	509	486	484	473	450	347	374	303
F-4G	101	102	100	102	101	82	92	73
F-15C	166	223	256	259	303	.	327	353
F-15A,B,D,E	355	336	333	332	343	279	295	322
F-16A	190	298	452	559	570	461	526	495
F-16B	58	67	76	101	.	82	90	78
F-16C	.	.	.	.	.	.	231	293
F-16D	.	.	.	.	.	.	36	43

<u>Summary</u>

This Chapter reviewed the sources that were used to solve the research questions. The nature and primary function of maintenance data was discussed, including the various reports that were generated from maintenance data. It was then discussed how the maintenance data was organized into independent and dependent variables that could be used in the CER model. The range of maintenance data was also anaylzed and is important to the research findings. The predictive ability of the model will depend on the range of data found for each of the independent and dependent variables. When actual values are used in the CER model that are within the range of data specified by this project, the model will produce accurate results for maintenance manhours. Chapter 4 will present the approach taken to develop a CER model and will discuss the statistical properties, as established in Chapter 2, of each model found.

IV. Model Development

Introduction

The purpose of this research was to develop a cost estimating relationship model for composite materials and to determine the significant cost drivers in developing the model. Maintenance data was used consisting of forty observations and nine attributes which were flight hours, sorties, landings, maintenance actions, failure types 1, 2, and 6, MTBR (or removal counts), and MTBM (or event counts). This chapter provides the steps taken to develop and evaluate the final models.

Assumptions

1. The data set was considered to be "good" - meaning there were no measurement errors or distortions in the data.

2. The independent variables were correct cost drivers.

3. The nature of the relationship between the independent variables and maintenance manhours is linear.

4. All observations are members of the population.

Approach

Selection of Variables. The maintenance data provided nine independent variables - flight hours, number of sorties, landings, maintenance actions, three types of failures, MTBR, and MTBM. All of these variables were considered to be drivers of the dependent variable, total maintenance manhours. Steps were then taken to determine which variable, or combination thereof, would be the most significant cost driver. The following steps were taken to ensure a logical approach was used.

1. The nine variable attributes were evaluated to determine if any other possible combinations could be used as cost drivers. In some instances, removal counts were used in place of MTBR. MTBM was also replaced with event counts. All together, nine new independent variables were developed and considered as potential cost drivers. Each new variable was given an abbreviated code for reference simplicity, as shown in Table VII. To begin, two new variables were developed from sorties. FS was used to represent flight hours divided by sorties and LS was used to represent landings divided by sorties. IC was developed to represent the sum of all indicator variables (discussed in paragraph 2). Additionally, LIC was used to represent landings multiplied by IC. FIC represented flight hours multiplied by IC, and SIC represented sorties multiplied by IC. Also, LMINSLIC was used to represent landings subtracted by LIC, FMINSFIC was flight hours subtracted by FIC, and SMINSSIC was sorties subtracted by SIC. When evaluating existing variables for possible new variables, it is important to develop new variables which are still relevant to the data set. Those new variables developed were relevant to the existing data set and are summarized in Table VII.

Table VII

"New " Variables Developed as Potential Cost Drivers

New Variable Code	New Variable Formula
1. FS	Flight hours divided by sorties

- continued -

Table VII - continued

New Variable Code		New Variable Formula
2.	LS	Landings divided by sorties
3.	IC	I1 + I2 + I3 + I4
4.	LIC	Landings * IC
5.	FIC	Flight hours * IC
6.	SIC	Sorties * IC
7.	LMINSLIC	Landings - LIC
8.	FMINSFIC	Flight hours - FIC
9.	SMINSSIC	Sorties - SIC

2. Because of the five different WUCs, indicator variables were used in the data set to determine the reaction of each WUC as a driver of maintenance manhours. Indicator variables quantitatively identified the qualitative attribute of different aircraft components and took on the values of 0 and 1. According to Neter, "a qualitative variable with "c" classes will be represented by c - 1 indicator variables, each taking on the values 0 and 1" (28: 330). Therefore, when using indicator variables, there is always one less indicator variable than there are qualitative categories. Since there were five WUCs, or qualitative categories, there were four indicator variables. In order to have a point of comparison, the WUC 14300 (F-4 stabilator system) was used as the baseline, or reference point, from which the other four WUCs would vary. WUC 14CBO was indicator variable 1 (I1), WUC 11JAC was indicator variable 2 (I2), WUC 11GKB was I3, and WUC 14CAD was I4 as indicated in Table VIII. Using indicator variables in the regression model allows the Y-intercept value (Bo) to vary; however, the

slope of the regression line can not change. When only the Y-intercept changes, the regression lines for each WUC would remain parallel. In this case, with the F-4 as baseline, the other WUCs would show a parallel regression line to be higher or lower from the F-4. In order to show changing slopes, interaction effects were introduced into the model, by including cross-product terms. These terms consisted of one of the four indicator variables and one of the independent variables. Table IX shows the interaction effects developed. Interaction effects allow the regression lines for the F-15 and F-16 WUCs to no longer be parallel to the baseline (27).

Table VIII

Indicator Variables for Each Work Unit Code

Aircraft	WUC	Indicator Variables I1	I2	I3	I4
F-4	14300	0	0	0	0
F-16	14CBC	1	0	0	0
F-16	11JAC	0	1	0	0
F-15	11GKB	0	0	1	0
F-15	14CAD	0	0	0	1

(28:329)

Table IX

Interaction Effects

Independent Variable	Indicator Variable	Interaction Effect Variable
Flight Hours (F)	I1	F*I1=IE1
Landings(L)	I1	L*I1=IE2
Sorties(S)	I1	S*I1=IE3

- continued -

Table IX - continued

Independent Variable	Indicator Variable	Interaction Effect Variable
FS	I1	FS*I1=IE4
LS	I1	LS*I1=IE5
F	I2	F*I2=IE6
L	I2	L*I2=IE7
S	I2	S*I2=IE8
FS	I2	FS*I2=IE9
LS	I2	LS*I2=IE10
F	I3	F*I3=IE11
L	I3	L*I3=IE12
S	I3	S*I3=IE13
FS	I3	FS*I3=IE14
LS	I3	LS*I3=IE15
F	I4	F*I4=IE16
L	I4	L*I4=IE17
S	I4	S*I4=IE18
FS	I4	FS*I4=IE19
LS	I4	LS*I4=IE20
		(28:335-336)

3. The next step was to regress each of the nine independent variables (exc[illegible]g indicator variables, interaction effect variables, and combination variables) against cost to examine their relationship as a significant cost driver. Significant cost drivers were found to be maintenance actions and events. Failure types, removal counts, and MTBR did not show significance because there were only six observations for these variables. Because of the lack of data for these variables, they were excluded as potential cost drivers. Although maintenance actions and events were the most significant cost drivers, they were excluded from the final model because it would first be necessary to predict maintenance actions and events before predicting maintenance manhours. At the conclusion of this step, it appeared the potential cost drivers for maintenance manhours would be flight hours, landings, sorties, the

indicator variables, the interaction effect variables, and the combination variables.

4. To determine the relative strength of the linear relationships between two variables, R2 values were determined for all possible pairwise relationships for 43 variables (including the nine independent variables, the indicator variables, interaction effect variables, and the new variables). It was found that events, maintenance actions, LMINSLIC, FMINSFIC, and SMINSSIC had the strongest linear relationship to cost, with R2 values of .977, .973, .97, .969, and .963 respectively. For comparison, R2 values were determined for 37 variables from composite data only. The variables with the strongest linear relationship to cost were similar to the data set including the metal aircraft component. Type six failures, maintenance actions, events, removals, FMINSFIC, SMINSSIC, and LMINSLIC had R2 values of .9546, .9153, .9053, .8967, .8521, .8503, and .8420 respectively. From the R2 data, events had the strongest linear relationship to cost when considering the entire data set. Alternatively, type six failures had the strongest linear relationship to cost for composite materials. Because events and maintenance actions were excluded as potential cost drivers, the completion of this step indicated that LMINSLIC, FMINSFIC, SMINSSIC would be potential cost drivers for the entire data set. The next step was to determine if there was another variable that could be entered with LMINSLIC, FMINSFIC, or SMINSSIC to produce a model that best predicted maintenance manhours.

5. A stepwise procedure, including all possible variables, was used to determine what other variables could be entered with LMINSLIC, FMINSFIC, and SMINSSIC. When LMINSLIC was run with all other variables,

the only variable entered was IE1, interaction effect variable composed of flight hours multiplied by indicator variable 1. For FMINSFIC, the only variable entered was also IE1. The variable FS was the only variable entered with SMINSSIC. Completion of this step indicated there were three possible cost estimating relationships that could predict maintenance manhours.

Model Selection. The three models produced from the stepwise procedures were analyzed with statistical criteria as explained in Chapter 2. Each model met the established criteria, excluding that criteria for the C.V. value. However, the use of each model will depend upon the user's preference towards working with flight hours, sorties, or landings. The variable that is more readily obtainable by the user will determine which model is used. The model with LMINSLIC and IE1 was also analyzed as a model consisting of LMINSLIC and IE2, interaction effect variable consisting of landings multiplied by indicator variable 2, for convenience of the user. Since IE2 is composed of landings, there is no need to also obtain flight hours, which would be required for IE1. There was no significant statistical difference between the LMINSLIC IE1/IE2 models, and their use depends on user preference.

The Full Models

Model LMINSLIC with IE1.

Y = bo + b1*LMINSLIC + b2*IE1 or
403.36 + .3621*L - .3621*LIC + .0206(F*I1)

F-4 I1=0 I2=0 Y = 403.36 + .3621*L

F-16 (14CBO) I1=1 I2=1 Y = 403.36 + .0206*F

F-16 (11JAC) F-15 (11GKB and 14CAD) I1=1 I2=0 Y = 403.36

Full Model Criteria Statistics.

F-value = 583.402 significance = .9999

R2 = .9725

*R2 = .9708

C.V. = 30.86%

t-value significance level:

bo (Y-intercept) = .2555

bl (LMINSLIC) = .9999

b2 (IE1) = .8930

95% confidence interval for B1: $.3399 \le B1 \le .3842$

95% confidence interval for B2: $-.0048 \le B2 \le .0459$

Condition Numbers:

LMINSLIC = 1

IE1 = 1.3

Tolerance Values:

LMINSLIC = .933

IE1 = .933

Outliers with respect to x:

Leverage value criteria was .167. Two observations, both from the F-16 (14CBO), exceeded the criteria indicating these observations were distant from the center of the x observations.

Outliers with respect to Y:

Studentized residual value criteria was 1.697. Three observations, all from the F-4, exceeded the criteria. These three observations indicated that the F-4 had outlying values for maintenance manhours, the dependent variable. All outlying observations had among the highest values for maintenance manhours in the entire data set, confirming the F-4 stabilator system used more maintenance manhours than the F-15 or

F-16.

Influential Observations:

Cooksd value criteria for the 50% F-distribution was .807 and 2.28 for the 90% F-distribution. A Cooksd value less than .8 indicated the observation was not influential, where an observation with a Cooksd greater than 2.28 meant the observation was influential. Cooksd values for all observations were less than .8, confirming none of the observations were influential. However, the largest Cooksd values were among the F-4 data, providing evidence that the F-4 data was exceptional when compared to the F-15 and F-16 data.

Condition Numbers:

A condition number of at least 10 would indicate collinearity. Both numbers for the independent variables were considerably lower than 10, providing evidence that there was no significant correlation between LMINSLIC and IE1.

Tolerance Values:

Another indicator of collinearity, a tolerance of 0 means there is high collinearity between variables, where a tolerance of 1 indicates there is no collinearity. Both tolerance values in this model are close to 1.

Hypothesis Testing. To determine if a reduced model would produce a better model than the full model, hypotheses tests were done on the regression coefficients. The decision rule is to reject Ho (the null hypothesis) if F-calculated is greater than the F-table value. The full-reduced model approach used an F-calculated and F-table value as follows:

$$\text{F-calc} = \frac{\dfrac{\text{Sum of Squared Errors (SSE - Reduced Model)} \ \text{Minus} \ \text{Sum of Squared Errors (SSE - Full Model)}}{\text{Degrees of Freedom (DF - Reduced Model)} \ \text{Minus} \ \text{Degrees of Freedom (DF - Full Model)}}}{\dfrac{\text{SSE (Full Model)}}{\text{DF (Full Model)}}}$$

F-table = (1- (1 - .9); DF(Numerator); DF(Denominator)

The F-calculated and F-table values were computed at the 90% level of confidence.

Ho: B1=B2=0
Ha: The two coefficients are nonzero
Reduced model Y = bo + LMINSLIC

F-calc = 2.746 F-table = 2.88

Decision rule: Reject Ho if F-calc > F-table. Since 2.746 is not greater than 2.88, Ho can not be rejected at the 90% level of confidence, or significance level of 10%. It is concluded that the regression coefficients B1 and B2 are not both significant and that the reduced model is a more useful predictor for maintenance manhours.

Ho: B1=B2=0
Ha: The two coefficients are nonzero
Reduced model Y = bo + IE1

F-calc = 1114.8 F-table (.9; 1; 33) = 2.88

Decision rule: Reject Ho at the 90% level of confidence, or significance level of 10%, and conclude that the regression coefficients B1 and B2 are significant. The full model is a useful predictor of maintenance manhours.

Summary. The statistics in this model satisfied all the model criteria established in Chapter 2, excluding that for the C.V. value. For this model, the C.V. value of 30.8% indicated that the data was located far from the center of the data, which was the mean of Y or 18,317. It was not unexpected that this data set would produce a high C.V.. The range of data for maintenance manhours was from 81 to 97,535 for all aircraft. With a mean value, or center point, of 18,317, data points with values of 81 and 97,535 were far from the center. This data set indicated that the probability of producing good estimates at the center of the data would not be likely because the data points were not located near the center of the data, but at the low and high ends of the data range. The F-value was high enough so that the probability of committing a Type I error was less than 1 in 10,000 or .0001. Because .0001 was small, it was possible to reject the hypothesis that all the regression coefficients were equal and conclude that the coefficients were significantly different from zero. Thus, it was very likely that the regression coefficients in this model were significant cost drivers for maintenance manhours. The R2 value exceeded the criteria of .9. The closer R2 was to 1, the stronger was the linear relationship between the independent and dependent variables, for this sample data set. For this model, 97% of the variability in the random variable Y was accounted for by the independent variables LMINSLIC and IE1. The *R2 value was very close to R2, which indicated that the independent variables were significant. *R2 is always less than the R2 value, but if the two are not close in value, according to the analyst's judgement, the independent variables are not considered to be significant. Since the R2 and *R2 values were considered to be close in value, the independent variables were judged to be significant cost drivers. One statistic which did not meet the established criteria was the C.V. value. With a C.V. value of 30.8%, it would not appear possible to get reliable values of the independent variables from anywhere in the data range. Since C.V. was considered high, reliable estimates of the independent variables could not be obtainec om the center of the data, and estimates would only become less reliable when farther from the center of the data. The 95% prediction interval bounds for the model was from 7239 to 29,396 maintenance manhours. The t-values for this model exceeded the established criteria, indicating that each independent variable was a significant cost driver. A 95% confidence interval for B1 (LMINSLIC) lied between .3399 and .3842. Since this interval did not contain 0, it was further concluded, at the .05 significance level, that B1 was not 0. However, the 95% confidence interval for B2 did contain 0, indicating that at the .05 significance level, B2 could be 0 and not be a significant cost driver. The reduced model, excluding IE1, showed that it would be a better predictor than the full model. This indicated that IE1 must be explaining such a small portion of the variability in Y, that it may not be significant. Concerning outlying observations, the F-16 (14CBO) had two observations that were indicated to be distant from the mean of the independent variables, or center of the data. Because only two observations were outliers with respect to x, and since they were not also outlying with respect to Y, they were not considered to be influencing the fit of the regression line. These outlying observations may have resulted from an unlikely event and it could not be determined they were caused by gross measurement error. The outlying observations with respect to Y were from the F-4. This data set indicated that maintenance manhours for the F-4 were significantly different when compared to the rest of the data. This was further confirmed by the fact that the F-4 had significantly higher maintenance manhours then the F-16 or F-15. According to this data set, as the number of landings increased, the maintenance manhours increased for the F-4. This indicated that landings significantly drove maintenance manhours for the F-4 stabilator system. For the F-16 horizontal stabilizer assembly, as the number of flight hours increased, maintenance manhours increased. This indicated that flight hours were a significant cost driver for this component. However, the maintenance manhours for the remaining composite materials on the F-15 and F-16 were not as affected by the number of landings or flight hours. Within the data range specified by this data set, the maintenance manhours for those composite materials would remain constant regardless of the number of landings or flight hours. The next model which follows, LMINSLIC with IE2, showed very similiar statistics to this model. The difference between the two models is that LMINSLIC with IE2 uses only number of landings, where the model just discussed used number of landings and flight hours.

Model LMINSLIC with IE2.

Y = bo + b1*LMINSLIC + b2*IE2 or
402.91 + .3621 * L - .3621 * LIC + .0265(L * I1)

F-4 I1=0 I2=0 Y = 402.91 + .3621*L

F-16 (14CBO) I1=1 I2=1 Y = 402.91 + .0265*L

F-16 (11JAC) F-15 (11GKB and 14CAD) I1=1 I2=0 Y = 402.91

Full Model Criteria Statistics.

F-value = 582.807 significance = .9999

R2 = .9725

*R2 = .9708

C.V. = 30.87%

t-value significance level:

bo (Y-intercept) = .2547

b1 (LMINSLIC) = .9999

b2 (IE2) = .8908

95% confidence interval for B1: $.3399 \leq B1 \leq .3843$

95% confidence interval for B2: $-.006 \leq B2 \leq .0594$

Conditions Numbers:

LMINSLIC = 1

IE2 = 1.3

Tolerance Values:

LMINSLIC = .9324

IE2 = .9324

Outliers with respect to x:

Two observations, both from the F-16 (14CBO), exceeded the leverage value criteria of .167. These observations were the same two as found in the LMINSLIC with IE1

Outliers with respect to Y:

The same three observations from the LMINSLIC with IE1 model, for the F-4, were found to be outliers.

Influential Observations:

Again, as with the previous model, there were no observations that exceeded the Cooksd value for being influential. But, as before, the F-4 had the highest Cooksd

values.

Condition Numbers:

The low condition numbers for both variable indicate there is no significant collinearity in the model.

Tolerance Values:

The high tolerance values evidence no collinearity.

Hypothesis Testing.

Ho: B1=B2=0
Ha: The two coefficients are nonzero
Reduced model Y = bo + LMINSLIC

F-calc = 2.71 F-table = (.9; 1; 33) = 2.88

Decision Rule: Reject Ho if F-calc > F-table. Since 2.71 is not greater than 2.88, Ho can not be rejected and it is concluded that at the 90% level of confidence, or significance level of 10%, the regression coefficients B1 and B2 are equal. Therefore, the reduced model will be a better predictor for the dependent variable.

Ho: B1=B2=0
Ha: The two coefficients area nonzero
Reduced model Y = bo + IE2

F-calc = 1112.75 F-table = (.9; 1; 33) = 2.88

Decision Rule: Reject Ho and conclude that the regression coefficients B1 and B2 are significant and that the full model is a useful predictor of maintenance manhours.

Summary. As with the previous model, the statistics in this model satisfied all the model criteria established in Chapter 2, excluding that for the C.V. value. Again, as before, the C.V. in this model was 30.8%. The data points were not located at the center of the data, making estimates at the center less likely to be accurate. Because the F-value was again high enough, the probability of committing a Type I error was less than 1 in 10,000 or .0001. It was therefore possible to reject the hypothesis that all the regression coefficients were equal and conclude that the coefficients were significantly different from zero. Thus, it was very likely that the regression coefficients in this model were significant cost drivers for maintenance manhours. The R2 and *R2 value for this model were exactly the same as before, resulting in 97% of the variability in the random variable Y being accounted for by the independent variables LMINSLIC and IE2. Since the R2 and *R2 values were considered to be close in value, the independent variables were judged to be significant cost drivers. One statistic which did not meet the established criteria was the C.V. value. With a C.V. value of 30.8%, it would not appear possible to get reliable values of the independent variables from anywhere in the data range. Because C.V. was considered high, reliable estimates of the independent variables could not be obtained from the center of the data, and estimates would only become less reliable when farther from the center of the data. The 95% prediction interval bounds for the model was from 7234 to 29,401 maintenance manhours. The t-values for this model exceeded the established criteria, indicating that each independent variable was a significant cost driver. A 95% confidence interval for B1 (LMINSLIC) lied between .3399 and .3843. Since this interval did not contain 0, it was further concluded, at the .05 significance level, that B1 was not 0. However, the 95% confidence interval for B2 (IE2) did contain 0, indicating that at the .05 significance level, B2 could be 0 and not be a significant cost driver. The reduced model, excluding IE2, showed that it would be a better predictor than the full model. This indicated that IE2 must be explaining such a small portion of the variability in Y, that it may not be significant. Concerning outlying observations, the F-16 horizontal stabilizer assembly had the same two observations as before that were indicated to be distant from the mean of the independent variables, or center of the data. Again, because only two observations were outliers with respect to x, and since they were not also outlying with respect to Y, they were not considered to be influencing the fit of the regression line. These outlying observations may have resulted from an unlikely event and it could not be determined they were caused by gross measurement error. The outlying observations with respect to Y were from the F-4. This data set indicated that maintenance manhours for the F-4 were significantly different when compared to the rest of the data which was confirmed by the significantly higher maintenance manhours for the F-4. According to this model, as the number of landings increased, the maintenance manhours increased for the F-4 and F-16 horizontal stabilizer assembly. This indicated that landings were a significant cost driver for these components. However, the maintenance manhours for the remaining composite materials on the F-15 and F-16 were not as affected by the number of landings. Within the data range specified by this data set, the maintenance manhours for those composite materials would remain constant regardless of the number of landings.

<u>Model FMINSFIC with IE1</u>.

Y = bo + b1*FMINSFIC + b2*IE1 or
362.27 + .3173*F - .3173*FIC + .0208(F*I1)

F-4 I1=0 I2=0 Y = 362.27 + .3172*F

F-16 (14CBO) I1=1 I2=1 Y = 362.27 + .0208*F

F-16 (11JAC) F-15 (11GKB and 14CAD) I1=1 I2=0 Y = 362.27

<u>Full Model Criteria Statistics</u>.

F-value = 565.741 significance = .9999

R2 = .9717

*R2 = .9699

C.V. = 31.32%

t-value significance level:

bo (Y-intercept) = .2268

b1 (FMINSFIC) = .9999

b2 (IE1) = .8913

95% confidence interval for B1: $.2976 \le B1 \le .337$

95% confidence interval for B2: $-.005 \le B2 \le .0465$

Condition Numbers:

FMINSFIC = 1

IE1 = 1.3

Tolerance Values:

FMINSFIC = .933

IE1 = .933

Outliers with respect to x:

The same two outliers, from the F-16 (14CBO), were found as discussed in the previous two models.

Outliers with respect to Y:

The same three outliers, from the F-4, were found in this model as discussed in the previous two models.

Influential Observations:

Again, there were no observations that were influential. But, as with the previous two models, the F-4 had the highest Cooksd values.

Condition Numbers:

No collinearity in the model.

Tolerance Values:

No collinearity in the model.

<u>Hypothesis Testing</u>.

Ho: B1=B2=0
Ha: The two coefficients are nonzero
Reduced model Y = bo + FMINSFIC

F-calc = 2.72 F-table = 2.88

Decision rule: Can not reject Ho at the 90% level of confidence.

Ho: B1=B2=0
Ha: The two coefficients are nonzero
Reduced model Y = bo + IE1

F-calc = 1081 F-table = 2.88

Decision rule: Reject Ho and conclude that the full model is a useful predictor of maintenance manhours.

<u>Summary</u>. The statistics in this model satisfied all the model criteria, excluding that for the C.V. value. Regardless of the model found in this research, the C.V. values were high because of the data range. The nature of the maintenance data that was found showed significant differences in the range of values for maintenanc manhours, which contributed to high C.V. values. The F-value was not as high as the previous two models, but was high enough so that the probability of committing a Type I error was less than 1 in 10,000 or .0001. Thus, it was very likely that the regression coefficients in this model were significant cost drivers for maintenance manhours. For this model, 97% (R2) of the variability in the random variable Y was accounted for by the independent variables FMINSFIC and IE1. The *R2 value was not as close to R2, which indicated that possibly one of the independent variables was not significant. When IE1 was in the model by itself, the R2 was .04 and *R2 was .015. With FMINSFIC in the model alone, R2 was.969 and *R2 was .968. In the full model, IE1 did not explain much of the variability of Y at all, so FMINSFIC explained almost 97% variability by itself. As with both previous models, the one statistic which did not meet the established criteria was the C.V. value. With a C.V. value at 31.3%, even higher than before, it would not appear

possible to get reliable values of the independent variables from anywhere in the data range. Since C.V. was considered high, reliable estimates of the independent variables could not be obtained from the center of the data, and estimates would only become less reliable when farther from the center of the data. The 95% prediction interval bounds for the model was from 7073 to 29,563 maintenance manhours. The t-values for this model exceeded the established criteria, indicating that each independent variable was a significant cost driver. A 95% confidence interval for B1 (FMINSFIC) did not contain 0, concluding at the .05 significance level that B1 was not 0. However, the 95% confidence interval for B2 did contain 0, indicating that at the .05 significance level, B2 could be 0 and not be a significant cost driver. The reduced model, excluding IE1, showed that it would be a better predictor than the full model. This indicated that IE1 explained such a small portion of the variability in Y, that it may not be significant. The extremely low R2 and *R2 values, as previously discussed, confirmed the low significance IE1 had as cost driver. Concerning outlying observations, the F-16 horizontal stabilizer assembly again had two observations that were indicated to be distant from the center of the data. Those observations were not considered to be influencing the fit of the regression line. These outlying observations probably resulted from an unlikely event. The outlying observations with respect to Y were again from the F-4. This model confirmed what the other models also showed, that the data set indicated maintenance manhours for the F-4 were significantly different when compared to the rest of the data. Accordingly, as the number of flight hours increased, the maintenance manhours increased significantly more for the F-4. For the F-16 horizontal stabilizer assembly, as the number of flight hours increased, maintenance manhours also increased. This indicated that flight hours were a significant cost driver for this component as well. However, the maintenance manhours for the remaining composite materials on the F-15 and F-16 were not as affected by the number of flight hours. Within the data range specified by this data set, the maintenance manhours for those composite materials would remain constant regardless of the number or flight hours.

<u>Model SMINSSIC with FS</u>.

Y = bo + b1*SMINSSIC + b2*FS or
-77455.9 + .4126*S - .4126*SIC + 58986.65*FS

F-4 I1=0 I2=0 Y = -77455.9 + .4126*S

F-16 (14CBO) I1=1 I2=1 Y = -77455.9 + 58986.65*FS

F-16 (11JAC) F-15 (11GKB and 14CAD) I1=1 I2=0 Y = -77455.9

<u>Full Model Criteria Statistics</u>.

F-value = 514.511 significance = .9999

R2 = .9689

*R2 = .9670

C.V. = 32.80%

t-value significance level:

bo (Y-intercept) = .9756

b1 (SMINSSIC) = .9999

b2 (FS) = .9781

95% confidence interval for B1: $.3734 \le B1 \le .4518$

95% confidence interval for B2: $8938.48 \le B2 \le 109{,}035$

Condition Numbers:

SMINSSIC = 1

FS = 2.926

Tolerance Values:

SMINSSIC = .3747

FS = .3747

Outliers with respect to x:

Four observations, all from the F-4, were found to be outliers. This is in comparison to the previous models, were all the outliers were from the F-16 (14CBO).

Outliers with respect to Y:

As with all previous models, outliers were found to be from the F-4.

Influential Observations:

One observation, from the F-4, had a Cooksd value greater than .8, indicating that observation could be influential.

Condition Numbers:

Condition numbers are lower than 10, indicating there should be no collinearity.

Tolerance Values:

Tolerance values are not 0, but are lower than in the other models. This indicates there is more collinearity in this model than the other three.

Hypothesis Testing.

Ho: B1=B2=0
Ha: The two coefficients are nonzero
Reduced model Y = bo + SMINSSIC

F-calc = 5.792 F-table = 2.88

Decision rule: Reject Ho and conclude that the regression coefficients are significant, at the 90% level of confidence, and the full model is a useful predictor of the dependent variable.

Ho: B1=B2=0
Ha: The two coefficients are nonzero
Reduced model Y = bo + FS

F-calc = 461.5   F-table = 2.88

Decision rule: Reject Ho and conclude that the full model is a useful predictor.

Summary. As with all the previous models, the statistics in this model satisfied established model criteria excluding that for the C.V. value. It was expected that the C.V. value would be similar to all the other models for the reasons previouly discussed. The F-value was lowest of all models, but still high enough so that the probability of committing a Type I error was less than 1 in 10,000 or .0001. Thus, it was very likely that the regression coefficients in this model were significant cost drivers for maintenance manhours. The R2 and *R2 values were lowest, but still exceeded the criteria of .9. For this model, 96.8% of the variability in the random variable Y was accounted for by the independent variables SMINSSIC and FS. The *R2 value was very close to R2, which indicated that the independent variables were significant, even though they were not explaining as much variability. The one statistic which did not meet the established criteria was the C.V. value. With the highest C.V. value of any model, at 32.8%, it would not appear possible to get reliable values of the independent variables from anywhere in the data range. Since C.V. was considered high, reliable estimates of the independent variables could not be obtained from the center of the data, and estimates would only become less reliable when farther from the center of the data. The 95% prediction interval bounds for the model was from 6543 to 30,093 maintenance manhours. The t-values for this model exceeded the established criteria, indicating that each independent variable was a significant cost driver. A 95% confidence interval for B1 (SMINSSIC) did not contain 0, so it was concluded, at the .05 significance level, that B1 was not 0. Like no other model, the 95% confidence interval for B2 also did not contain 0, indicating that at the .05 significance level, B2 was a significant cost driver. The reduced models did not show they would be better predictors than the full model. This indicated that both independent variables must be explaining the variability in Y. Concerning outlying observations, the F-4 stabilator system had four observations that were indicated to be distant from the mean of the independent variables. Because these observations were outliers with respect to x, and not also outlying with respect to Y, they were not considered to be influencing the fit of the regression line. The outlying observations with respect to Y were also from the F-4. For this model, all outlying observations were from the F-4. This indicated that the F-4 maintenance manhours were most significantly influenced by number of sorties than the rest of the data. The F-16 horizontal stabilizer assembly was also affected by sorties, but not to the same extent as the F-4. However, the maintenance manhours for the remaining composite materials on the F-15 and F-16 were not affected by the number of sorties. Within the data range specified by this data set, the maintenance manhours for those composite materials would remain constant regardless of the number of sorties.

Conclusion

This thesis is not recommending any particular model. The purpose of this research was to determine cost drivers of composite materials, which was discussed in this Chapter. However, there also exists other cost drivers which could significantly affect maintenance manhours. It must be remembered that the models developed were dependent upon the maintenance data available.

V. Model Usage

Summary

The models developed in this research paper determined that the most significant cost drivers of maintenance manhours were landings, flight hours, and sorties. Four models were discussed that reflected these significant cost drivers and can be selected for predicting maintenance manhours for specific aircraft components according to the user's discretion. All the models met the established statistical criteria established in Chapter 2, except for the C.V. value. Because of the range of data, the data points did not lie close to the mean of the independent variable causing the C.V. value to be greater than the 20% criteria. Because of the nature of the maintenance data used for this project, having low and high extremes from the mean Y value, it was not unexpected that the C.V. values in the four models were large numbers.

Model LMINSLIC with IE1 showed the best statistics of all models, but LMINSLIC with IE2 was very close. For this model, 97% of the variability in Y was accounted for by the independent variables. The R2 and *R2 values were close, indicating that the independent variables were both significant in explaining the dependent variable.However, the 95% confidence interval for IE1 contained 0, indicating that it alone may not be explaining that much of the variability in Y. As a result, the reduced model showed to be a better predictor of maintenance manhours. Outliers with respect to x came from the F-16 (14CBO) observations and they were not considered to be influencing the fit of the regression line. The outlying observations with respect to Y were from the F-4. The data indicated that maintenance manhours for the F-4 were significantly different from the rest of the data. This was confirmed by the fact that the F-4 had significantly higher maintenance manhours than the F-15 or F-16. This model showed that as the number of landings increased, the maintenance manhours increased for the F-4. Landings were a significant cost driver for the F-4 maintenance manhours. For the F-16 horizontal stabilizer assembly, flight hours were a significant cost driver. However, the maintenance manhours for the remaining composite parts on the F-16 and F-15 were not affected by the number landings or flight hours. Within the data range specified by this data set, maintenance manhours f . these composite parts would remain constant regardless of the number of landings or flight hours.

The LMINSLIC with IE2 required only landing data as an input to the equations, where the previous model required not only landing data, but flight hours. This model had very similar statistics to the model with IE1 and should produce similar predictive results. The *R2 and R2 values were the same as before, resulting in 97% of the variability in the random variable Y being accounted for by the independent variables. As with the previous model, the 95% confidence interval for IE2 contained 0, indicating that this variable did not explain much of the variability in Y. The reduced model, without IE2, showed to be a bet er predictor than the full model. The outlying observations for this model were the same as discussed in the previous model. According to this model, as landings increased, so did maintenance manhours for the F-4 and F-16 horizontal stabilizer assembly. However, the maintenance manhours for the . aining composite materials on the F-16 and F-15 were constant within the specified range of data.

A model with only flight hours, FMINSFIC with IE1 was developed with good statistics, according to the criteria. For this model, 97% of the variability in Y was accounted for by the independent variables. However, the R2 and *R2 values were as close as with the other two models, which indicated that possibly one of the variables was not a significant cost driver. This proved to be the case, for when IE1 was in the model alone, it did not explain the variability in Y at all. Therefore, FMINSFIC explained almost 97% of the variability by itself. The reduced model also showed it would be a better predictor than the full model. The outliers with respect to x were again the same observations from the F-16 horizontal stabilizer assembly. Outliers with respect to x were from the F-4, as with the previous two models. This models showed that flight hours were a significant cost driver for the F-4 and F-16 horizontal stabilizer assembly. However, the remaining composite materials on the F-16 and F-15 showed constant maintenance manhours, within the data range.

The final model, SMINSSIC with FS, showed statistics not as good as the other models, although the criteria was at least met. This model was the only one, however, in which the full model was shown to be a better predictor of maintenance manhours than the reduced models. Although the other models had better statistics, reduced models could have been better at predicting than the full models. This indicated that with the other models, the IE1 or IE2 variable explained very little more in the variability of Y. For this model the outlying observations with respect to x and Y were from the F-4. The F-4 maintenance manhours were most significantly influenced by number of sorties than the rest of the data. The F-16 horizontal stabilizer assembly was also affected by sorties, but not to the same extent as the F-4. Within the data range specified, the remaining composite materials on the F-16 and F-15 had constant maintenance manhours.

Overall, the research results showed a relationship between increases in landings, flight hours, and sorties and increases in maintenance manhours for the F-4 stabilator. The data proved that the F-4 stabilator required more maintenance manhours than the composite materials on the F-15 and F-16. Simply, this means that the more the F-4 flies, the more maintenance will be required for the stabilator. The F-16 horizontal stabilizer assembly also showed a relationship between increases in landings, flight hours, and sorties and increases in maintenance manhours, but not to the same extent as the F-4. The other composite materials on the F-16 and F-15 did not show a relationship between increases in the independent variables and increases in maintenance manhours. As long as the F-16 and F-15 flies within the range of data found for this project, those composite parts will require the same number of maintenance manhours, as specified by the equations from the models.

This project confirmed the need to adjust maintenance manhours according to the flying mission required of the different aircraft. For example, if all the 3 types of aircraft flew the same number of hours in a month, the F-4 stabilator would require the most maintenance manhours than the other aircraft components discussed herein. The F-16 horizontal stabilizer assembly would require the next highest amount of maintenance time. However, as long as the F-16 and F-15 flew within the range of data from this project, the remaining composite parts would require the constant number of maintenance manhours according to the model equations. Of course, each aircraft type, and individual aircraft within type, does not have the same flying mission. It then becomes important to adjust maintenance manpower to accommodate changes in flying missions. If the F-4 is going to increase or decrease flying time, than maintenance time and manpower will have to be adjusted. The same holds for the F-16 horizontal stabilizer assembly, as maintenance time for this composite part is related to increases in landings, flight hours, and sorties. The maintenance time for the remaining composite parts are not affected by changes in landings, flight hours, and sorties. Therefore, unless flying missions are decreased or increased beyond the relevant range, maintenance time and necessary manpower will remain constant.

The model that becomes most accepted by users will depend upon the data available to them. Because all the aircraft used in this project belonged to Tactical Air Command (TAC), the model most likely to be of great use would be the model SMINSSIC with FS. Monthly flying programs stipulated by TAC are based on sortie counts. Since sortie counts must be forecasted on a regular basis, the model using sortie count data would be easier for TAC personnel to apply.

Once a model is chosen and maintenance manhours for a particular aircraft component predicted, those manhours can be used to forecast necessary maintenance personnel levels in the field. Statistical data from this research has shown that the F-4 stabilator system will fail more frequently than comparable component parts on the F-15 and F-16. Because of this, there will be a greater demand for F-4 maintenance manpower. The models can be used to determine to what extent manpower levels should be adjusted.

Areas for Future Research

Time constraints limited research to the area of field level maintenance only. It would also be interesting to determine the extent of depot maintenance required for composite materials. The data used in this project showed that maintenance manhours for composite materials was significantly less when compared to the metal materials. But, lower maintenance manhours for field level repairs does not necessarily imply the same for depot level maintenance. It is possible that depot level maintenance could be more expensive for composites.

Battle damage repair of composites should also be considered for future research. With extensive use of composite materials in new aircraft, it becomes necessary to determine how these aircraft can be repaired in war. Damage to composite materials can not be simply repaired in the field as can be done to metals. During the Vietnam War, for example, the F-4 could be "patched" with inexpensive tape and sent back to fly. This can not be done with composite materials. Alternative methods and materials of repair would have to be developed.

Appendix: List of Definitions

1. Aggregates A mixture of different materials separable by mechanical means. Any inert material as sand or gravel added to a cementing agent to make concrete.

2. Boron Essentially a non-metal occurring naturally as in borax or boric acid.

3. Carbon An element that forms organic compounds in combination with hydrogen and oxygen. It occurs in a pure state as the diamond and in an impure state as charcoal.

4. Ceramic Family of oxides, nitrides, carbides and the element of carbon. Their crystalline versatile properties are easily combined with nonmetal materials.

5. Commingled hybrid yarns A combination of two or more composite materials entwined to form a yarn like thread.

6. Composite material Structural materials of metal alloys or plastics with built-in strengthening agents in the form of filaments, foils, or flakes of a strong material.

7. Development Costs All costs required to develop a system before committing it to production. Encompasses engineering design, manufacture of test articles, and testing.

8. Epoxy An oxygen atom bound to two atoms already connected, usually carbon atoms, to form a ring. Also called epoxy resin - any class of substances formed as polymer from epoxy chemicals, such as adhesives.

9. Graphite A form of carbon which occurs in crystalline forms, and more commonly in masses of flakes or granules.

10. Life Cycle Cost All costs necessary to develop, produce, operate, support and dispose of a weapon system.

11. Maintainability A characteristic of design and installation that an item will be retained in or restored to a specified condition within a given period of time when maintenance is performed as prescribed.

12. Matrix The base material with which various reinforcements, fillers, or additives are combined using techniques suitable for producing a composite material. A matrix material may be metallic, polymeric (plastic), or ceramic.

13. Mean Manhours to Repair (MMR) The total corrective base level manhours divided by the total on-equipment corrective maintenance events for a given period.

14. Mean Time Between Corrective Maintenance Actions (MTBMA) Average time between maintenance actions expressed in hours excluding all general support.

15. Mean Time Between Maintenance (MTBM) Total life units divided by the total number of maintenance hours for a specific period.The average time between on-equipment corrective maintenance events including inherent, induced, and no-defect maintenance actions.

16. Mean Time Between Removal (MTBR) The total number of system life units divided by the total number of items removed from that system during a stated period of time. Excludes removals performed to facilitate other maintenance and removals for product improvement.

17. Milestone 0 Concept Exploration phase to evaluate alternative solutions of a projected military requirement.

18. Milestone I Demonstration and Validation phase to further define system characteristics.

19. Milestone II Full-Scale Development phase to perform development and testing.

20. Milestone III Production/Deployment phase to schedule system procurement production quantities and the phasing-in of full Air Force support.

21. Milestone IV Operations and Support phase to review operational readiness and support objectives.

22. Milestone V Operations Support phase to determine 5 to 10 years after initial deployment whether the system's operational effectiveness warrants the system be upgraded or replaced.

23. Operating and Support The final cost element in a system's life cycle.

24. Polycrystalline A rock or metal composed of more than one crystal.

25. Polymer A compound derived either by the addition of many smaller molecules or by the condensation of many smaller molecules as with nylon.

26. Polymeric Compounds having the same elements and combined in the same proportions by weight.

27. Production Costs Costs associated with the fabrication, assembly, and delivery of a system.

28. Reinforcements Various materials used to reinforce or strengthen the matrix material to form a composite material.

29. Reliability The probability that an item will perform a required function under specified conditions for a specified period of time.

30. Resin An organic substance used in the making of varnishes or plastics.

31. Silicon-carbide A hard material made by heating carbon with silicon to form bricks, abrasive wheels, and cement.

32. Thermoplastic A plastic which becomes soft and pliable whenever heated, without any change in the inherent properties.

33. Thermoset Any plastic that sets when heated and can not be reheated.

34. Viscosity The property of a fluid that resists the force tending to cause the fluid to flow.

35. Whisker Extremely fine, discontinously grown single crystals defined in size by cross-sectional area in square microns (the millionth part of a meter) rather than by diameter.

36. Work Unit Code (WUC) Five characters to identify the system, subsystem, line replaceable unit, or component/shop replaceable unit on which work is required.

Bibliography

1. Adler, Terry R. Class Handouts Distributed in Cost 669, Introduction to Cost Analysis. School of Systems and Logistics, Air Force Institute of Technology (AU), Wright-Patterson AFB OH, July 1988.

2. "Aircraft Builders Register Slow Progress in Advanced Composites Applications," Aviation Week and Space Technology, 125: 50,55,57,59,62 (29 September 1986).

3. Andrews, Richard A. Class Handouts Distributed in SYS 225, Acquisition Logistics. School of Systems and Logistics, Air Force Institute of Technology (AU), Wright-Patterson AFB OH, February 1987.

4. "ASD Composite Cost Roadmap," Prepared by Management Consulting and Research, Inc., Project TR-8706/14-1 I1G11 (March 1988).

5. Booher, Margaret, RM Engineer. Personal Interview. ALD/EER, Wright-Patterson AFB OH, 26 June 1989.

6. Chawla, K.K. "Composite Materials - ICCMV, "Journal of Metals, 37: 25-28 (December 1985).

7. Clemens, S. R. and others. "Thermoplastic Hybrid Yarns for High-Performance Composites," Materials Engineering, 105: 27-30 (March 1988).

8. Cole, Tim and Eppinger, Josh. "Air Power 2000," Popular Mechanics, 164: 70-74 (December 1987).

9. "Composite Materials - A Bright Future in Aerospace Applications," Metallurgia, 53: 366,368 (August 1986).

10. Curry, Ernest E. Short Cut Cost Estimating Methodology for High Performance Fighter Aircraft. Wright-Patterson AFB OH, May 1971.

11. Defense Document Center. Predictive Operations and Maintenance Cost Model. Report AFAL-TR-78-49; Vol II. Hunt Valley,Maryland: April 1978.

12. DeMario, William F. "New World for Aerospace Composites," Aerospace America, 24: 36-40 (October 1985).

13. Department of the Air Force. Maintenance and Operational Data Access System, User's Manual. April 1987.

14. Department of the Air Force. Quick Reference Guide to Maintenance Data Collection (MDC). November 1986.

15. Department of the Air Force. Technical Manual Aircraft Maintenance Work Unit Code Manual. T.O. 1F-4D-06 July 1988.

16. Department of the Air Force. Technical Manual Aircraft Maintenance Work Unit Code Manual. T.O. 1F-15A-06 April 1988.

17. Department of the Air Force. Technical Manual Aircraft Maintenance Work Unit Code Manual. T.O. 1F-16-06 February 1988.

18. Department of the Air Force. USAF R and M 2000 Process. July 1988.

19. Executive Office of the President, Office of Management and Budget. Budget of the US Government, Fiscal Year 1987. Washington: US Government Printing Office (no date).

20. English, Lawrence K. ed. "Fabricating the Future With Composite Materials," Material Engineering, 4: 15 (September 1987).

21. English, Lawrence K. ed. "SAMPE 88: Materials - Pathway to the Future," Materials Engineering, 105: 57-60 (June 1988).

22. Griffiths, David. "Military Aircraft: How Much High Tech is Enough?," Business Week, 2998: 76,80 (May 11,1987).

23. Hashin, Z. "Analysis of Composite Materials - A Survey," Journal of Applied Mechanics, 50: 481-505(September 1983).

24. Heaney, John E. "Materials: Technology Keeps Pace With Needs," Aviation Week and Space Technology, 125: 67,70,74,76,78,82,89+ (13 October 1986).

25. Massey, H.G. and Marks, K.E. Life Cycle Analysis Procedures and Techniques: An Appraisal and Suggestions for Future Research. Rand P-6031. Santa Monica CA October 1977.

26. Myer, Captain Patricia, Cost Analyst. Personal Interview. ASD/ACCC, Wright-Patterson AFB OH, 21 June 1989.

27. Murphy, Richard. Class lecture in COST 671, Defense Cost Modeling. School of Systems and Logistics, Air Force Institute of Technology (AU), Wright-Patterson AFB OH, Fall Quarter 1988.

28. Neter, John and others. Applied Linear Regression Models. Homewood Illinois: Richard D. Irwin, Inc.,1983.

29. Rehg, Virgil. Class Handouts Distributed in QMT 372, Reliability Course. School of Systems and Logistics, Air Force Institute of Technology (AU), Wright-Patterson AFB OH, March 1989.

30. Reinhardt, Theodore, Chief, Systems Support Division/ Engineering Branch. Personal Interview. AFWAL/MLSE, Wright-Patterson AFB OH, 13 July 1988.

31. Revellin-Falcoz, B. Combat Aircraft of the Year 2000 FTD-ID(RS)T-0252-85. Foreign Technology Division, 28 March 1985.

32. Scala, E. Composite Material for Combined Functions. Rochelle Park New Jersey: Hayden Book Company, Inc., 1973.

33. Stang, Henrik. "Strength of Composite Materials With Small Cracks in the Matrix," Internatinal Journal of Solids and Structures, 22: 1259-1277 (Number 11 1986).

34. The Air Force Systems Command Cost Estimating Hand Book Series. Reading MA (no date).

35. "US Air Force Develops Advanced Composites," Materials Engineering, 44: 1208, 1214, 1217-1218 (September 1986).

36. Vinson, J. R. and Sierakowski, R. L. The Behavior of Structures Composed oı Composite Materials. Dordrecht: Martinus Nijhoff Publishers, 1986.

37. Yetter, Jay, Maintenance Policy Division. Personal Interview. HQAFLC/MMDA, Wright-Patterson AFB OH, 24 March 1989.

VITA

Captain Diana Marie Morosi-Bock [redacted] She graduated from high school in Cherry Hill, New Jersey, in 1976. After completing a four year enlistment with the Air Force, she attended Drexel University from which she received the degree in Business Administration in June 1982. Upon graduation, she received a commission in the USAF through the ROTC program. Her first assignment was with the Air Force Audit Agency detached at Nellis AFB, Nevada. From there she served the Audit Agency as Special Projects Officer and Auditor at Wright-Patterson AFB, Ohio, prior to entering the School of Systems and Logistics, Air Force Institute of Technology, in May 1988.

[redacted]

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) AFIT/GCA/LSY/89S-3	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION School of Systems and Logistics 6b. OFFICE SYMBOL (If applicable) AFIT/LSQ	7a. NAME OF MONITORING ORGANIZATION
6c. ADDRESS (City, State, and ZIP Code) Air Force Institute of Technology Wright-Patterson AFB OH 45433-6583	7b. ADDRESS (City, State, and ZIP Code)
8a. NAME OF FUNDING/SPONSORING ORGANIZATION 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State, and ZIP Code)	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO. / PROJECT NO. / TASK NO / WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification)
COST EFFECTIVENESS OF COMPOSITE MATERIALS ON THE F-15 AND F-16 AIRCRAFTS

12. PERSONAL AUTHOR(S)
Diana M. Bock, B.S., Capt, USAF

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
MS Thesis	FROM ______ TO ______	September 1989	97

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Composite Materials, Maintenance Data Collection System, Multiple Regression Analysis
11	04		

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Thesis Advisor: Terry R. Adler
Instructor
Department of Systems Acqusition Management

Approved for public release: IAW AFR 190-1.

Larry W. Emmelhainz

LARRY W. EMMELHAINZ, Lt Col, USAF 11 Oct 89
Director of Research and Consultation
Air Force Institute of Technology (AU)
Wright-Patterson AFB OH 45433-6583

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED
22a. NAME OF RESPONSIBLE INDIVIDUAL Terry R. Adler, Instructor	22b. TELEPHONE (Include Area Code) (513) 255-3355 22c. OFFICE SYMBOL LSY

DD Form 1473, JUN 86 Previous editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE

UNCLASSIFIED

The purpose of this research was to determine the cost effectiveness of composite materials by determining the significant cost drivers in a cost estimating model. Based on a review of historical literature and interviews, it was originally suspected that composite materials were not as cost effective as metal structures in terms of maintenance manhours.

The models developed in this project revealed that number of landings, flight hours, and sorties counts were the most significant cost drivers for maintaining the F-4 stabilator system, a metal structure, and the composite materials found on the horizontal and vertical stabilizers of the F-15 and F-16 aircrafts. The stabilator system on the F-4 was most respondent to the three cost drivers, as this structure required significantly more maintenance manhours than either the F-15 or F-16 parts. The F-16 horizontal stabilizer assembly was also sensitive to the cost drivers found, as this composite part had more maintenance manhours than the other three composite parts. The F-16 skins, vertical stabilizer assembly and the F-15 torque box, vertical stabilizer and honeycomb assembly, torque box, horizontal stabilator assembly showed that regardless of the number of landings, flight hours, or sortie counts, the maintenance manhours remained constant, within the range of data for this project.